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Ozonation and Manganese Greensand Filtration for Iron and Manganese Removal from a Municipal Groundwater Supply

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OZONATION AND MANGANESE GREENSAND FILTRATION FOR IRON AND MANGANESE REMOVAL FROM A MUNICIPAL GROUNDWATER SUPPLY

by
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OZONATION AND MANGANESE GREENSAND

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This thesis is approved as a creditable and independent investigation by a candidate for the degree, Master of Science, and is acceptable as meeting the thesis requirements for this degree. Acceptance of this thesis does not imply that the conclusions reached by the candidate are necessarily the conclusions of the major department.

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Thesis Advisor and
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This thesis is dedicated to my wife, Polly.

ACKNOWLEDGEMENTS

The author wishes to express sincere appreciation to his research partner, Mr. James P. Housiaux who helped construct the pilot plant, collect samples, and interpret data. Jim studied the regenerative capabilities of the ozone/manganese greensand pilot system. Appreciation also is extended to Dr. Dwayne A. Rollag for his guidance and technical assistance throughout the investigation, Dr. David Hilderbrand for his cooperation and prompt assistance in the use of the atomic absorption spectrophotometer, and Dr. James N. Dornbush and Mr. Delvin DeBoer for their encouragement.

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INTRODUCTION

Nature of the Problem

Iron and manganese are common contaminates in water supplies and have been studied extensively. The nature of the problem is well summarized by Stoebner (1)(3):

> Iron and manganese are relatively abundant elements in the earth's continental crust, existing in soils primarily as insoluble ferric and manganic compounds such as Fe_2O_3, FeS_2, and MnO_2.... Even though those compounds are not dissolved by pure rain water, they will be dissolved by groundwater under certain conditions. In the soils, carbon dioxide (CO_2) is released as a byproduct of the bacterial decomposition of organic matter.... The carbon dioxide is then absorbed by the groundwater and exists in equilibrium with carbonic acid.... Under anaerobic conditions the iron- and manganese-bearing materials are reduced by the slightly acidic water to their soluble ferrous and manganous forms: $Fe(HCO_3)_2$, $FeSO_4$, $FeCl_2$, $Mn(HCO_3)_2$, $MnSO_4$, and $MnCl_2$.... Since iron and manganese will remain soluble only in the absence of dissolved oxygen, groundwaters usually contain much higher concentrations of these metals than do surface waters.... However, once groundwater is exposed to oxidation, the soluble ferrous (Fe^{+2}) and manganous (Mn^{+2}) compounds will be converted to ferric (Fe^{+3}) and manganic (Mn^{+4}) precipitates such as $Fe(OH)_3$ and MnO_2....
>
> In its 1962 water quality standards, the United States Public Health Service (USPHS) recommended maximum iron and manganese concentrations of 0.3 and 0.05 mg/l respectively.... Furthermore, the goal of the American Water Works Association (AWWA) is to maintain levels of iron and manganese below 0.05 and 0.01 mg/l respectively.... Since both elements are necessary for human nutrition and since their intake through drinking water is an insignificant fraction of the body's requirement, iron and manganese are limited for esthetic and economic reasons rather than because of physiological hazards....

The presence of iron and manganese in concentrations exceeding the USPHS drinking water standards is objectionable for the following reasons:

1. The precipitation of iron and manganese alters the appearance of water, turning it a turbid yellow-brown to black....

2. The deposition of these precipitates will also cause brown to black stains on laundry and porcelain plumbing fixtures....

3. Iron and manganese deposits in water mains are frequently resuspended by increased flow rates, resulting in high turbidities....

4. Several groups of higher bacteria (including Crenothrix and Leptothrix) have the unique power to consume dissolved iron as food. Colonies of these bacteria will, in turn, reduce the effective area of distribution pipes, clog meters, and obstruct valves....

5. When these microorganisms die and slough off, taste and odor problems may occur....

6. Iron and manganese themselves, in concentrations greater than a few milligrams per liter, will impart a metallic or bitter taste to water....

7. Iron- and manganese-bearing waters may impart a disagreeable color or taste to beverages and may form a dark deposit on vegetables during cooking....

8. Water containing iron and manganese is unsuitable for many industrial processes including paper manufacturing, dyeing, bleaching, and film processing....

OBJECTIVES

Stoebner (1) and Schjodt (2) both used a pilot plant which treated raw water with ozone gas for the oxidation of iron and manganese and then passed the treated water through an anthracite coal filter. Both agree that the degree of iron and manganese oxidation was greatly affected by changes in ozone dosage but was not greatly affected by changes in detention time. Both also experienced limited filter runs between backwashing because of iron and manganese breakthrough in the filter effluent.

Kirscherman (3) used a pilot plant that involved aeration, potassium permanganate ($KMnO_4$) treatment, basin detention, and filtration through a dual media (manganese greensand overlaid with anthracite coal). Kirscherman found that the manganese greensand was capable of reducing total and soluble iron and manganese to within USPHS recommended limits when passing only aerated water through the filter. In time, the contact bed lost its property for exchanging cations, therefore, regeneration was needed to restore this property. $KMnO_4$ was used for regeneration. $KMnO_4$ was also used for chemical oxidation treatment by continuous application.

The pilot plant used in this study involves treating raw water with ozone gas and passing the treated water through a coal/manganese greensand filter. The research objectives of this study are to:

1. determine whether or not a shorter detention time would become a significant factor in the degree of iron and manganese oxidation;
2. compare the iron and manganese removal capacities of the coal filter and the coal/manganese greensand filter;
3. compare the ozone and potassium permanganate pilot systems with respect to iron and manganese removal efficiency;
4. determine the feasibility of converting the Brookings East Water Treatment Facility from a chemical treatment plant to an ozone/greensand system.

LITERATURE REVIEW

Background

The rate of oxidation of iron and manganese depends upon the type and concentration of the oxidizing agent, pH, alkalinity, organic content, and presence of catalysts.

The concentrations of iron and manganese found in natural waters are frequently limited by the solubility of their carbonates. Waters of high alkalinity have lower iron and manganese concentrations than waters of low alkalinity (4). The solubility of manganese ($MnCO_3$) is higher than that of iron ($FeCO_3$).

The oxidation of manganese by dissolved oxygen is slower than the oxidation of iron and is unacceptably slow at a pH less than approximately 9.5 (5). The pH level for oxidation of iron should be 7.5 or higher (6). Organic substances in the water can create complexes and chelates with iron and manganese ions holding them in the soluble state requiring higher pH levels for precipitation to occur (4)(6).

It has been a general assumption that iron and manganese are first oxidized (iron from ferrous $-Fe^{+2}$ to ferric $-Fe^{+3}$ and manganese from manganous $-Mn^{+2}$ to manganic $-Mn^{+4}$) and then precipitated as hydroxides ($Fe(OH)_3$) or oxides (MnO_2) as follows (4)(5)(7):

$$O_2 + 4Fe^{+2} + 10H_2O = 8H^+ + 4Fe(OH)_3 \qquad (1)$$

$$O_2 + 2Mn^{+2} + 2H_2O = 4H^+ + 2MnO_2 \qquad (2)$$

The oxidation of Mn^{+2} is an autocatalytic reaction accelerated by MnO_2 surfaces. Morgan suggested the reaction steps in oxygenation be broken down as follows (4)(7):

$$Mn^{+2} + 0.5O_2 \underline{\text{slow}} \; MnO_2 \qquad (3)$$

$$Mn^{+2} + MnO_2 \underline{\text{fast}} \; Mn^{+2}MnO_2 \qquad (4)$$

$$Mn^{+2}MnO_2 + 0.5O_2 \underline{\text{slow}} \; 2MnO_2 \qquad (5)$$

Olson and Twardowski (8) have shown, however, the iron precipitate may possibly be $FeCO_3$ in carbonate hard waters rather than $Fe(OH)_3$ when simple aeration and precipitation is practiced. $FeCO_3$ apparently is stable against oxidation to Fe^{+3} at a pH less than 9. Olson and Twardowski found the filtration of $FeCO^{+3}$ to be substantially faster than $Fe(OH)_3$ in a membrane filtration apparatus. They also concluded that ferrous carbonate precipitates as crystals, whereas ferric hydroxide precipitates as amorphous gelatinous masses which plug a filter cake more rapidly.

For reasons previously stated, more efficient methods of oxidation are needed to precipitate Mn^{+2} as MnO_2 within reasonable time periods and typical pH ranges common to water utility practices.

Ozone gas (O_3) has a very high oxidation potential and is considered an effective disinfectant. It is more soluble in water than ordinary oxygen but is relatively unstable and will spontaneously revert back to oxygen. Heat will accelerate the decomposition of ozone (9).

Organic matter in the Brookings groundwater is negligible therefore the primary ozone demand is utilized by iron and manganese. The following equations represent the reactions of ozone with the metals (7):

$$O_3 + 2Fe^{+2} + 5H_2O = O_2 + 4H^+ + 2Fe(OH)_3 \quad (6)$$

$$O_3 + Mn^{+2}\ H_2O = O_2 + 2H^+ + MnO_2 \quad (7)$$

Based upon a comprehensive review of the literature by Stoebner (1), Schjodt (2) pointed out some of the advantages and disadvantages of treating groundwater with ozone.

As an alternative disinfectant for a groundwater supply, ozone has six distinct advantages:

1. Ozone precipitates iron and manganese.
2. Ozone reduces the potential for trihalomethane formation.
3. Ozone reduces the chlorine demand of water.
4. Ozone is unsurpassed for destroying bacteria, viruses, pathogens, and spores.
5. Ozone effectively reduces taste, odor, and color.
6. Ozone destroys organic pollutants including pesticides.

As an alternative disinfectant for a groundwater supply, there are four factors associated with ozone that may be considered disadvantages:

1. Ozone does not provide a lasting residual to guard against recontamination in the distribution system.

2. Ozone decomposes very rapidly making long contact time between the water and the disinfectant difficult to achieve.

3. Ozone must be produced on site and relatively elaborate generating equipment is required.

4. Ozonation generally has a higher total cost than does chlorination.

Potassium permanganate ($KMnO_4$) is a chemical oxidant commonly used in water treatment practices for the removal of iron and manganese. The following equations illustrate the reactions (4) (7)(10):

$$MnO_4 + 3Fe^{+2} + 7H_2O = 5H^+ + MnO_2 + 3Fe(OH)_3 \qquad (8)$$

$$2MnO_4 + 3Mn^{+2} + 2H_2O = 4H^+ + 5MnO_2 \qquad (9)$$

Manganese greensand is a purple-black filter media commonly used for iron and manganese removal. It is prepared industrially by treating the mineral glauconite with manganese solutions giving it a manganese dioxide (MnO_2) surface capable of removing soluble iron and manganese. Anthracite coal is usually placed over the manganese greensand to increase filter runs. The coal removes most of the insolubles reducing the problem of plugging the greensand.

Potassium permanganate is used to regenerate manganese greensand. The contact bed will lose its MnO_2 coating to soluble iron

and manganese. The bed will eventually become exhausted and regeneration will be required to avoid breakthrough of solubles. Batches of $KMnO_4$ can be added to the system intermittently whenever the media needs regeneration or a dosage of $KMnO_4$ can be added continuously as a chemical oxidant.

Disadvantages to the intermittent regenerative-batch process are the possibility of soluble manganese leakage when the bed is nearly degenerated, and the expensive waste of excess $KMnO_4$ needed for regeneration (6). The continuous feed of $KMnO_4$ ahead of the filter can overcome these disadvantages and reduce the frequency of greensand regeneration. The following equations illustrate the degeneration and regeneration reactions for the manganese zeolite process (6):

$$Z.MnO_2 + \begin{matrix} Fe^{+2} \\ Mn^{+2} \end{matrix} = Z.Mn_2O_3 + \begin{matrix} Fe^{+3} \\ Mn^{+3} \\ Mn^{+4} \end{matrix} \qquad (10)$$

$$Z.Mn_2O_3 + KMnO_4 = Z.MnO_2 \qquad (11)$$

Case-Studies

Kjos, Furgason and Edwards of the chemical engineering department at the University of Idaho, Moscow, Idaho (11), have conducted a pilot plant study to determine the ozone dosage necessary to reduce iron and manganese from the Moscow municipal groundwater supply. The raw water used in this study contained 9.54 mg/l iron and 1.21 mg/l manganese. Treating the raw water with an ozone dosage of 8 mg/l, using a contact time of 30 seconds, reduced the soluble iron and manganese to below USPHS limits. Filtration studies using sand and

coal/sand media indicate filter breakthrough occurred anywhere from 2 to 7 hours since backwashing, using filtration rates of 1.6 and 2.5 gpm/ft^2.

In 1980 Stoebner (1) provided a comprehensive account of a pilot plant study conducted at the City of Brookings, South Dakota to determine, in part, the feasibility of using ozonation followed by anthracite coal filtration for removal of iron and manganese. The filter media and filtering rate (2 gpm/ft^2) employed during the pilot study were identical to those used at the Brookings East Water Treatment Plant. The raw groundwater supply contained 4.5 mg/l iron and 0.64 mg/l manganese. Stoebner concluded the following:

a) The degree of iron and manganese oxidation was significantly affected by changes in ozone dosage but was not greatly affected by changes in detention time ranging from 5 to 30 minutes.

b) Iron was oxidized at an ozone dosage of 2 mg/l whereas manganese was not significantly oxidized until 4 mg/l was reached. Manganese is apparently more difficult to oxidize than is iron to within USPHS standards.

c) Increasing the ozone dosage above 4 mg/l did not substantially improve the degree of iron and manganese oxidation.

d) The anthracite filter medium was not very effective in removing the iron and manganese flocs formed by oxidation with ozone. The maximum practical length of filter runs would be about 10 hours based on breakthrough and not head

loss through the filter which was only 6 inches (0.15 m) at breakthough.

Figures 1 and 2 indicate the pilot system was only capable of 10-hour filter runs before iron and manganese breakthrough occurred. The decrease in soluble manganese with time can be explained by the autocatalytic effect created by accumulated MnO_2 precipitate in the filter.

In 1983 Schjodt (2) provided an account of the same pilot plant feasibility study conducted at the City of Sioux Falls, South Dakota. The coal filter media and filtering rate (2 gpm/ft^2) employed during the pilot study were identical to those used by Stoebner. The raw groundwater supply contained 3.9 mg/l iron and 2.3 mg/l manganese. Schjodt concluded the following:

a) The degree of iron and manganese oxidation was greatly affected by changes in ozone dosage but was not greatly affected by changes in detention time ranging from 5 to 30 minutes.

b) Iron was oxidized to within the USPHS limit; manganese was not. At dosages of 8 mg/l and beyond, soluble permangante was formed. Therefore, something between 4 mg/l and 8 mg/l would be the optimum ozone dosage.

c) The anthracite filter medium was effective in removing the insoluble iron and manganese to within USPHS limits. The maximum practical length of filter run would be about 20 hours having a total head loss of 2.4-feet (0.74-m).

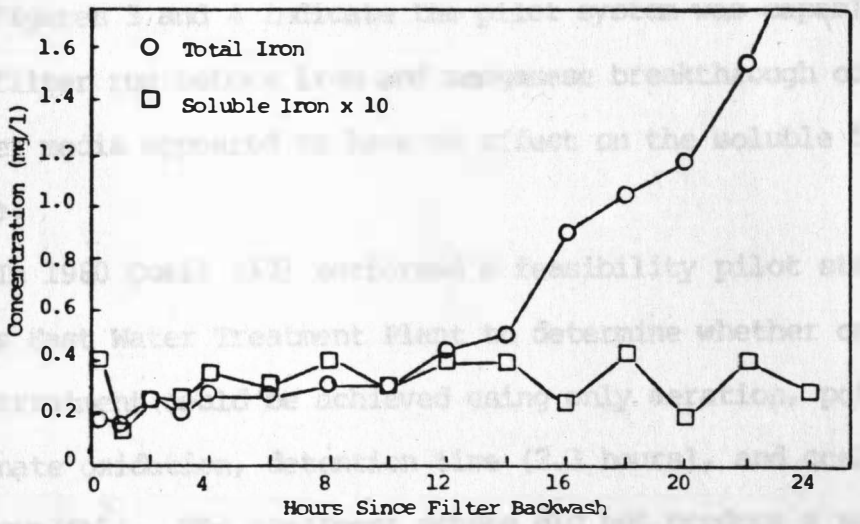

Figure 1. Iron Concentrations in the Filter Effluent Versus Time Since Backwash - Stoebner (1)

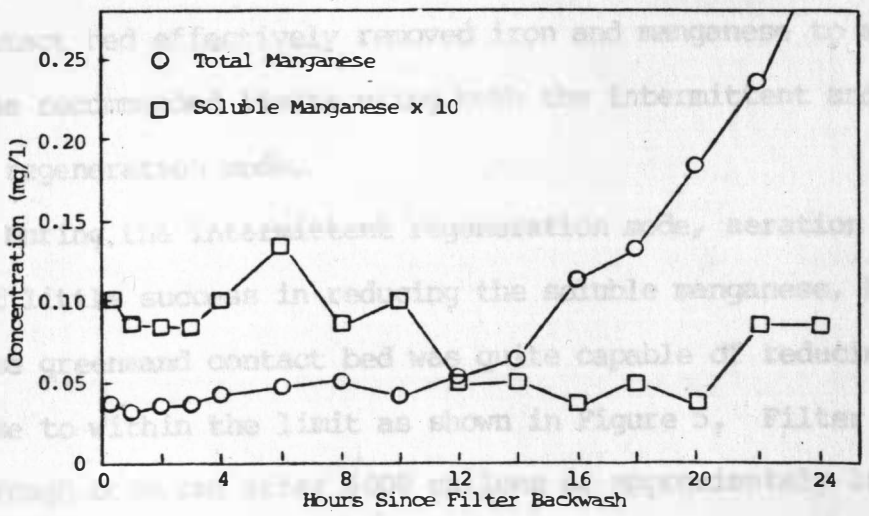

Figure 2. Manganese Concentrations in Filter Effluent Versus Time Since Backwash - Stoebner (1)

Figures 3 and 4 indicate the pilot system was capable of a 20-hour filter run before iron and manganese breakthrough occurred. The filter media appeared to have no effect on the soluble iron and manganese.

In 1980 Quail (12) performed a feasibility pilot study at the Brookings East Water Treatment Plant to determine whether or not the desired treatment could be achieved using only aeration, potassium permanganate oxidation, detention time (2.3 hours), and coal filtration (2 gpm/ft^2). The treatment scheme did not produce a water meeting the recommended limit for manganese.

In 1984 Kirschenman (3) submitted a study which supplemented the work performed by Quail. In this pilot study the treatment scheme was modified by replacing the filter coal media with a dual (coal/manganese greensand) media. Kirschenman found that the manganese greensand contact bed effectively removed iron and manganese to a level below the recommended limits using both the intermittent and continuous regeneration mode.

During the intermittent regeneration mode, aeration and detention had little success in reducing the soluble manganese, however the manganese greensand contact bed was quite capable of reducing soluble manganese to within the limit as shown in Figure 5. Filter breakthrough occurred after 6000 gallons or approximately 10.5 days. Backwashing was performed every two days. The total head loss generated three days after backwashing was 1.55-feet (1.47-m).

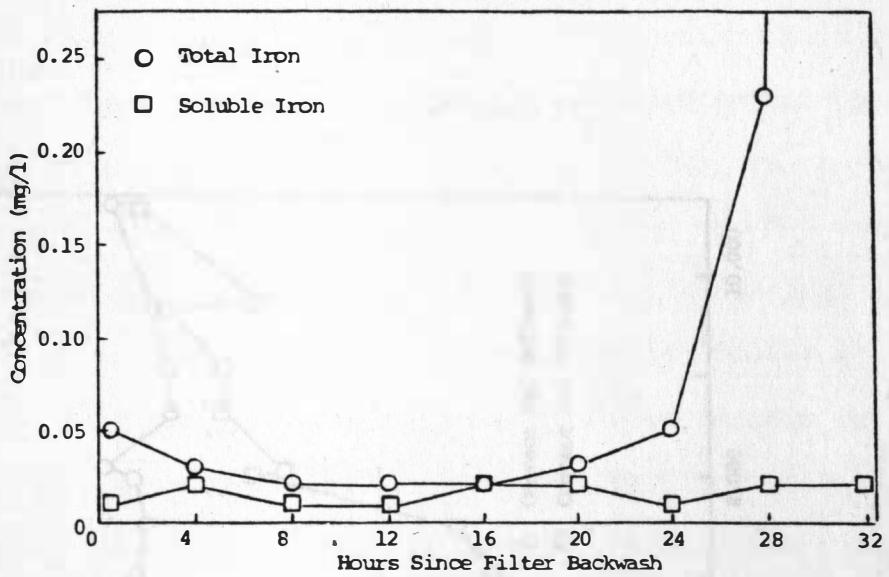

Figure 3. Iron Concentrations in the Filter Effluent Versus Time Since Backwash - Schjodt (2)

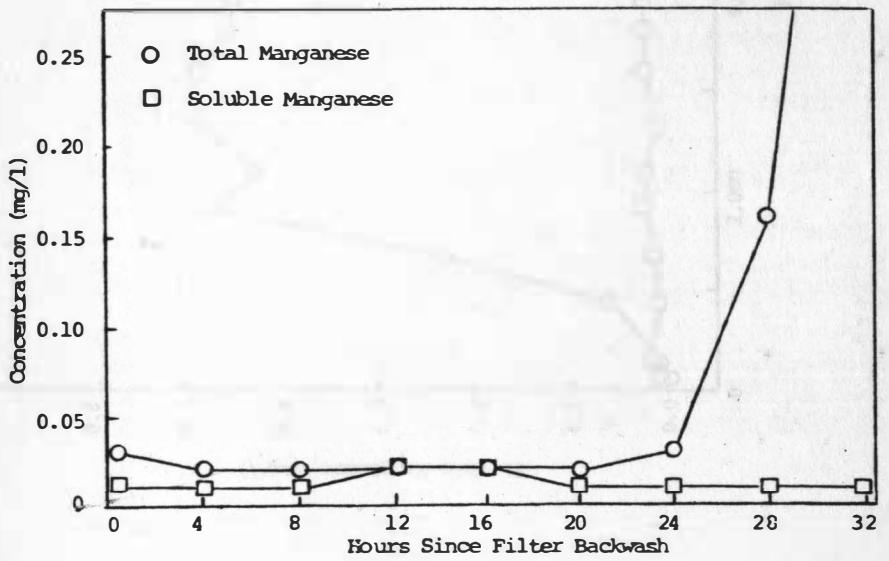

Figure 4. Manganese Concentrations in Filter Effluent Versus Time Since Backwash - Schjodt (2)

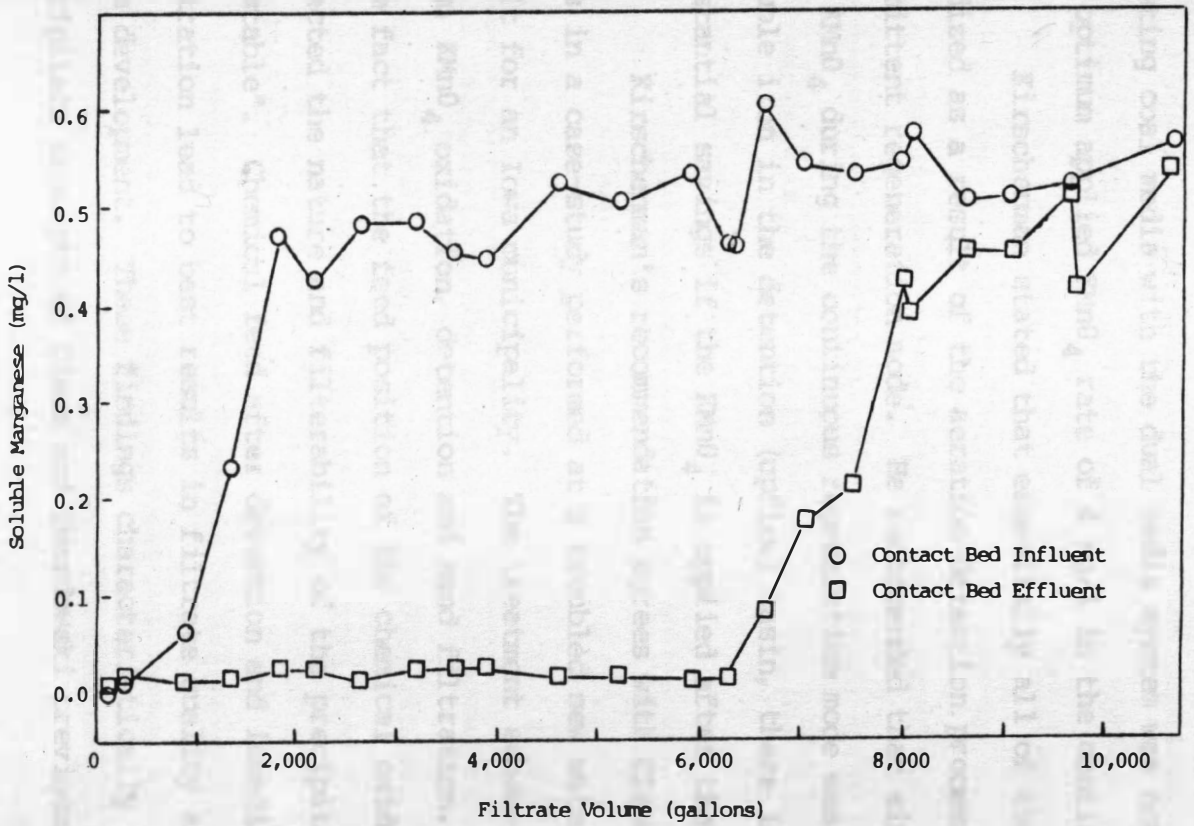

Figure 5. Contact Bed Influent and Effluent Soluble Manganese Concentrations During Intermittent Regeneration Mode - Kirschenman (3)

Backwashing for the continuous regeneration mode was performed once each day. The total head loss generated after about 32 hours (762 gallons) was 4.84-feet (1.47-m). For Brookings, replacing the existing coal media with the dual media system was not economical at the optimum applied $KMnO_4$ rate of 4 mg/l in the continuous mode.

Kirschenman stated that essentially all of the iron was being oxidized as a result of the aeration-detention process during the intermittent regeneration mode. He recommended that since a portion of the $KMnO_4$ during the continuous regeneration mode was oxidizing soluble iron in the detention (upflow) basin, there is potential for a substantial savings if the $KMnO_4$ is applied after the basin.

Kirschenman's recommendation agrees with Cleasby's (5) findings in a case-study performed at a troubled new water treatment plant built for an Iowa municipality. The treatment scheme involved aeration, $KMnO_4$ oxidation, detention and sand filtration. Cleasby stated, "the fact that the feed position of the chemical oxidant drastically affected the nature and filterability of the precipitate is irrefutable". Chemical feed after detention and immediately prior to filtration lead to best results in filtrate quality and lower head loss development. These findings characteristically reinforce the precipitate concepts of Olson and Twardowski previously discussed.

METHODS AND MATERIALS

Description of Pilot Plant

The pilot plant used in this study consisted of an air-preparation system, an ozone generator, one contact column, a constant-head tank, and a filter. A simplified schematic flow diagram of the entire pilot plant is shown in Figure 6.

The air-preparation system, ozone generator, and contact column were all supplied by Emery Industries, Inc., Cincinnati, Ohio, and have been described in detail by DeBoer (15) and summarized by Stoebner (1) and Schjodt (2).

Figure 7 presents a photograph of the air-preparation system and ozone generator. Atmospheric air was first filtered and then compressed to 100 psig (690 kpa) then cooled and stored in a pressure tank. Next, oil, moisture and dust were removed from the air by flowing consecutively through a pre-filter, desiccator, and coalescer. At this point, pressure was reduced to 15 psig (100 kPa) for ozone generation.

The ozone generator operates on a constant frequency of 60 Hz and has a variable voltage power supply. Within the tube-type generator are three stainless steel tubes surrounded with a jacket of cooling water. A slightly smaller diameter tubular glass dielectric, as shown pictorially in Figure 8, is inside each of the three tubes having a small annular space between the dielectrics and the inner surface of the stainless steel tubes. A stainless steel screen is inside each glass tube and serves as a high voltage electrode. As the

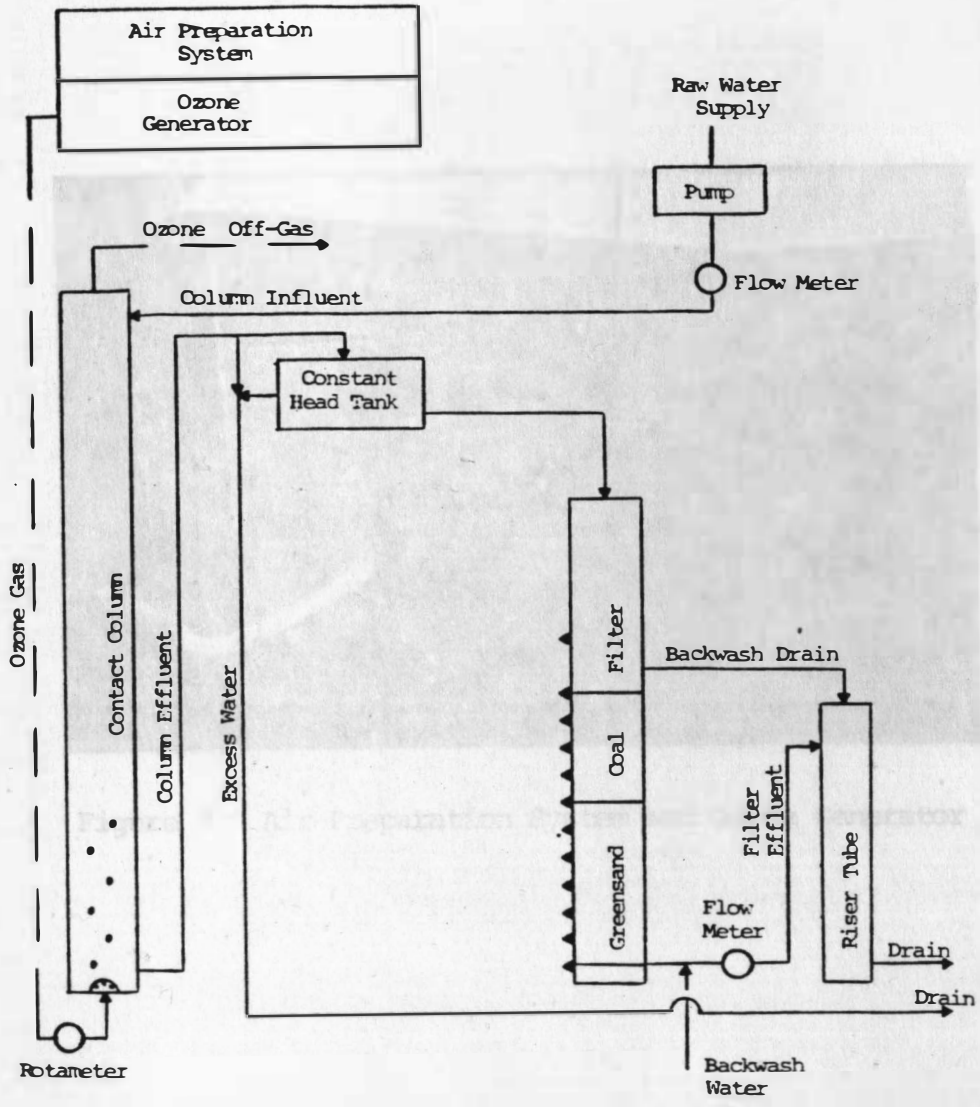

Figure 6. Schematic Diagram of Pilot Plant

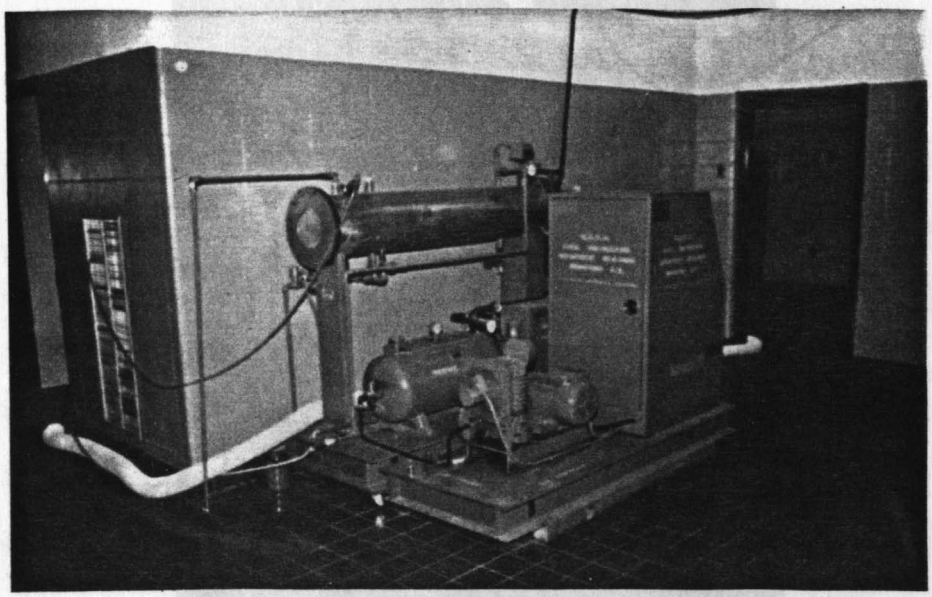

Figure 7. Air-Preparation System and Ozone Generator

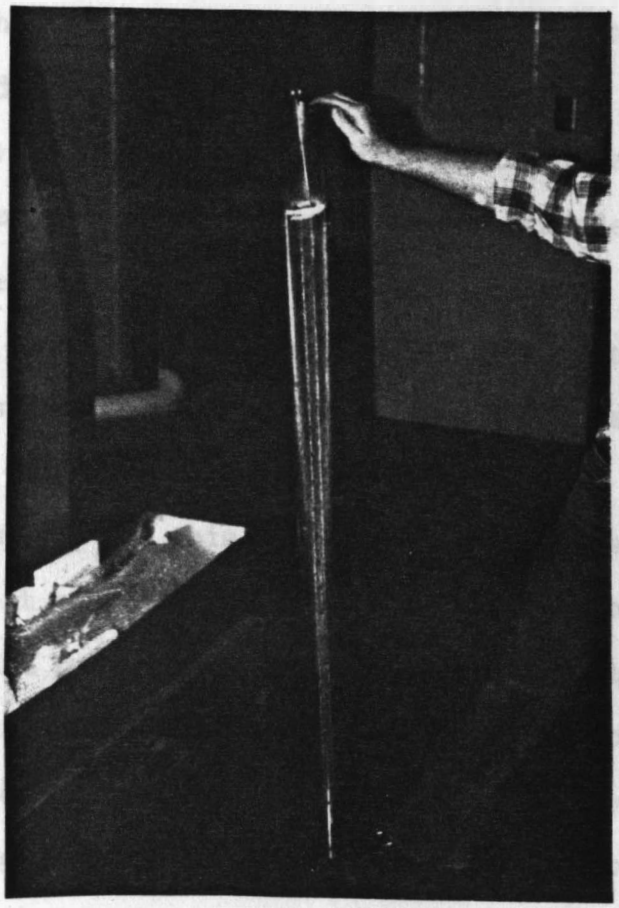

Figure 8. Ozone Generator Dielectric

prepared air travels down the annular space, a corona across the space converts a small percentage of oxygen to ozone. The ozonized air from the generator is then routed to the contact column.

Figure 9 shows two stainless steel contact columns. Each column has an inside diameter of 6-inches (15.2-cm) and a total height of 16-feet (4.88-m). Ozonized air from the generator was injected at the bottom of the contact columns through porous stainless steel diffusers. Due to the relatively short contact times used in this experiment, only one contact column was used. Flow of the ozonized air to the diffuser was regulated with a ball valve and rotameter located at the base of the column as illustrated in Figure 10.

Raw water supply for this study came from the aerator by-pass line of the treatment plant. Figure 11 shows the variable-speed positive-displacement pump and flow meter used for regulating and measuring the raw water flow to the top of the contact column, thus providing the desired contact time. The water flowed down the column counter-currently against the diffusing bubbles, back up to the top of the column via a 2-inch (5.08-cm) PVC pipe where an adequate portion of the flow spilled into the constant-head tank located above the filter. Excess ozone off-gas not absorbed by the water was discharged through the top of the contact column via tygon tubing and routed to an exhaust vent leading outdoors.

Figure 12 presents a photograph of the acrylic constant-head tank used. The sole purpose of the constant-head tank was to provide a constant flow of treated water to the filter. The tank was not

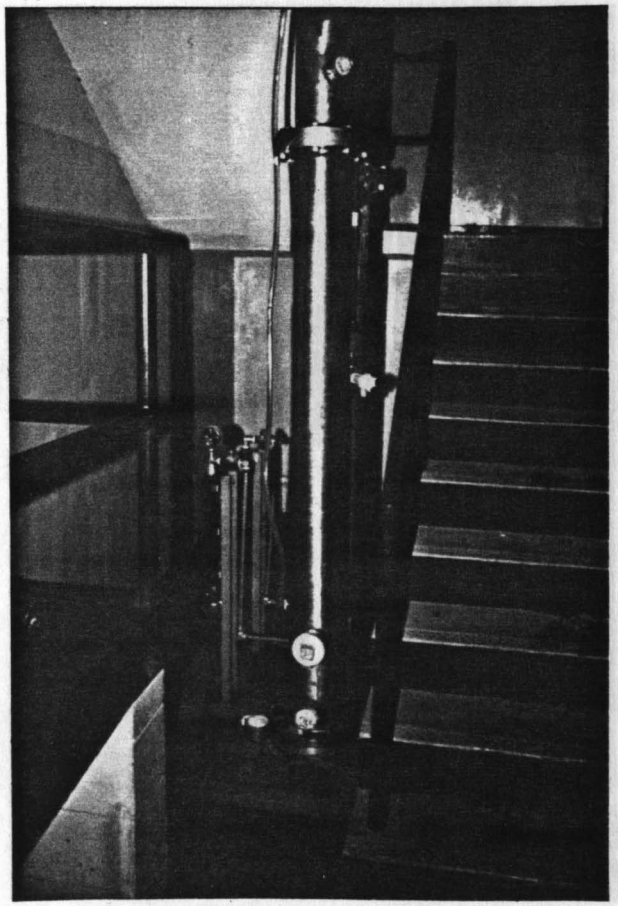

Figure 9. Contact Columns

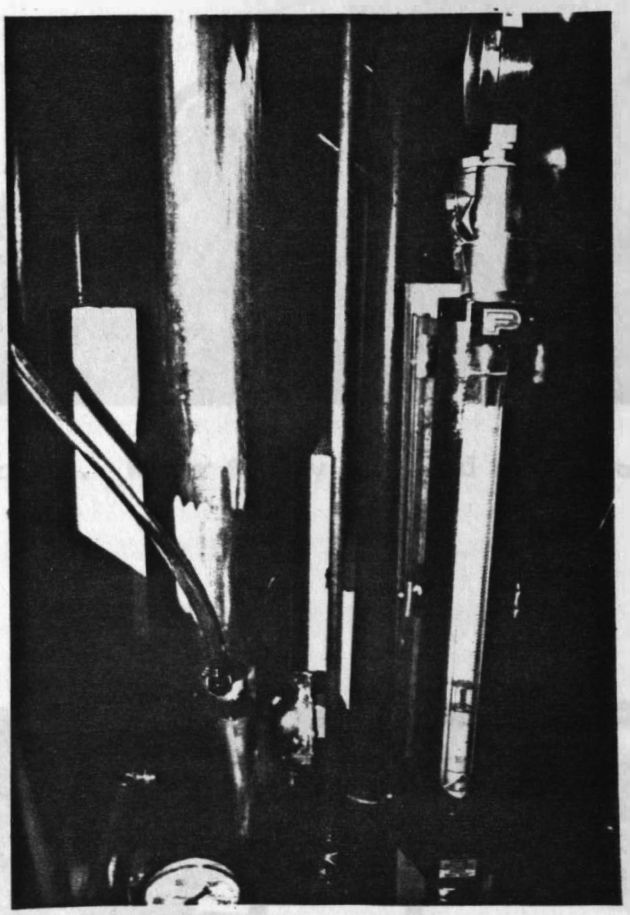

Figure 10. Regulating Valves and Meters to Ozone Diffusers

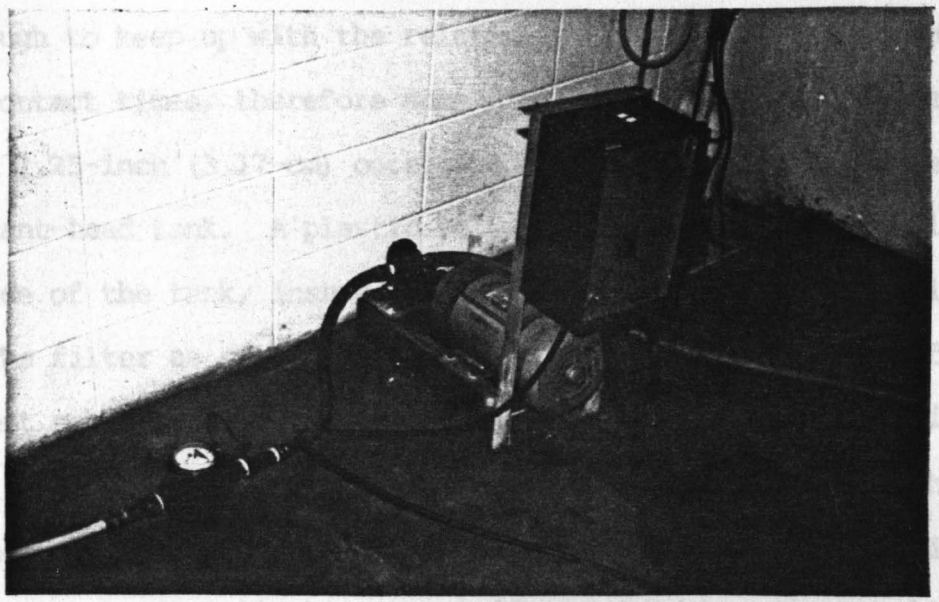

Figure 11. Water Supply Pump and Flow Meters

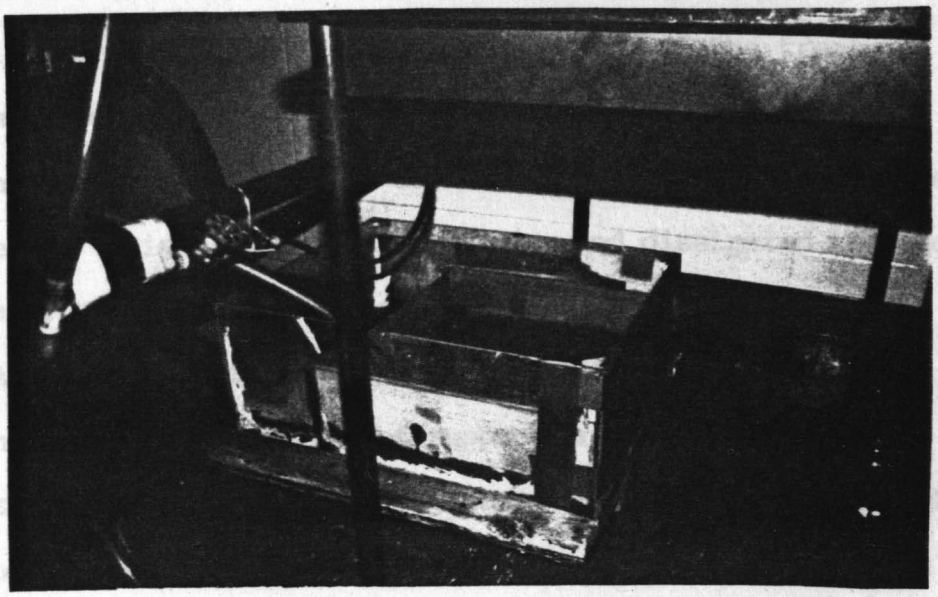

Figure 12. Constant-Head Tank

large enough to keep up with the relatively large flows needed for the desired contact times, therefore some flow was diverted and wasted through a 1.25-inch (3.17-cm) corrugated plastic hose before entering the constant-head tank. A plastic valve located on the bottom discharge side of the tank, insured the desired flow rate to the filter.

The filter as shown pictorally in Figure 13, consisted of a transparent schedule 80 PVC column with an inside diameter of 6-inches (15-cm). The underdrain for the filter is an aluminum box 9-inches (23-cm) high with side dimensions of 12-inches (31-cm). The 16-inch (41-cm) square base at the bottom provides stability. A removable side panel facilitated cleaning of the underdrain. The effluent line from the filter included: valving for the backwash line, a Hersey-Sparling water meter, and a plastic riser tube with a diameter of 0.75-inches (1.9-cm). A 0.75-inch (1.9-cm) garden hose with a check valve was connected to the discharge line of the treatment plant's high service pump station to obtain backwash water. The riser tube maintained a minimum water depth of seven inches (18 cm) over the filter media. This eliminated air binding and dissipated the energy of the water as it cascaded into the filter.

A dual anthracite coal-manganese greensand filter medium was used with 12-inches (30.48-cm) of support gravel. A total of 18-inches (45.72-cm) of manganese greensand overlaid with 12-inches (30-cm) of ripened No. 1 anthracite coal were placed in seperate layers over the gravel. Figure 14 provides a detailed sectional view of the pilot filter which was also used by Kirschenman. Table 1

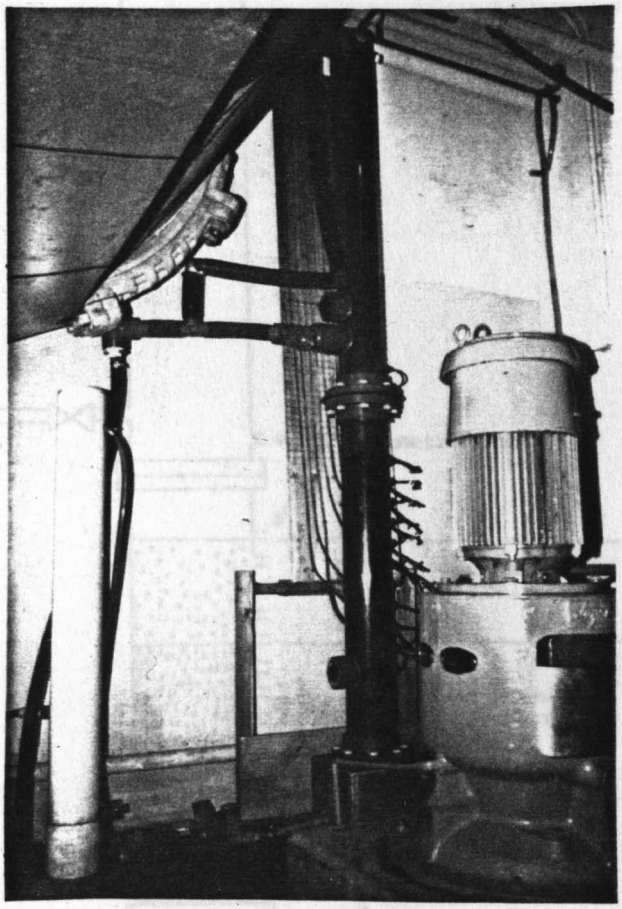

Figure 13. Dual Media Pilot Filter System

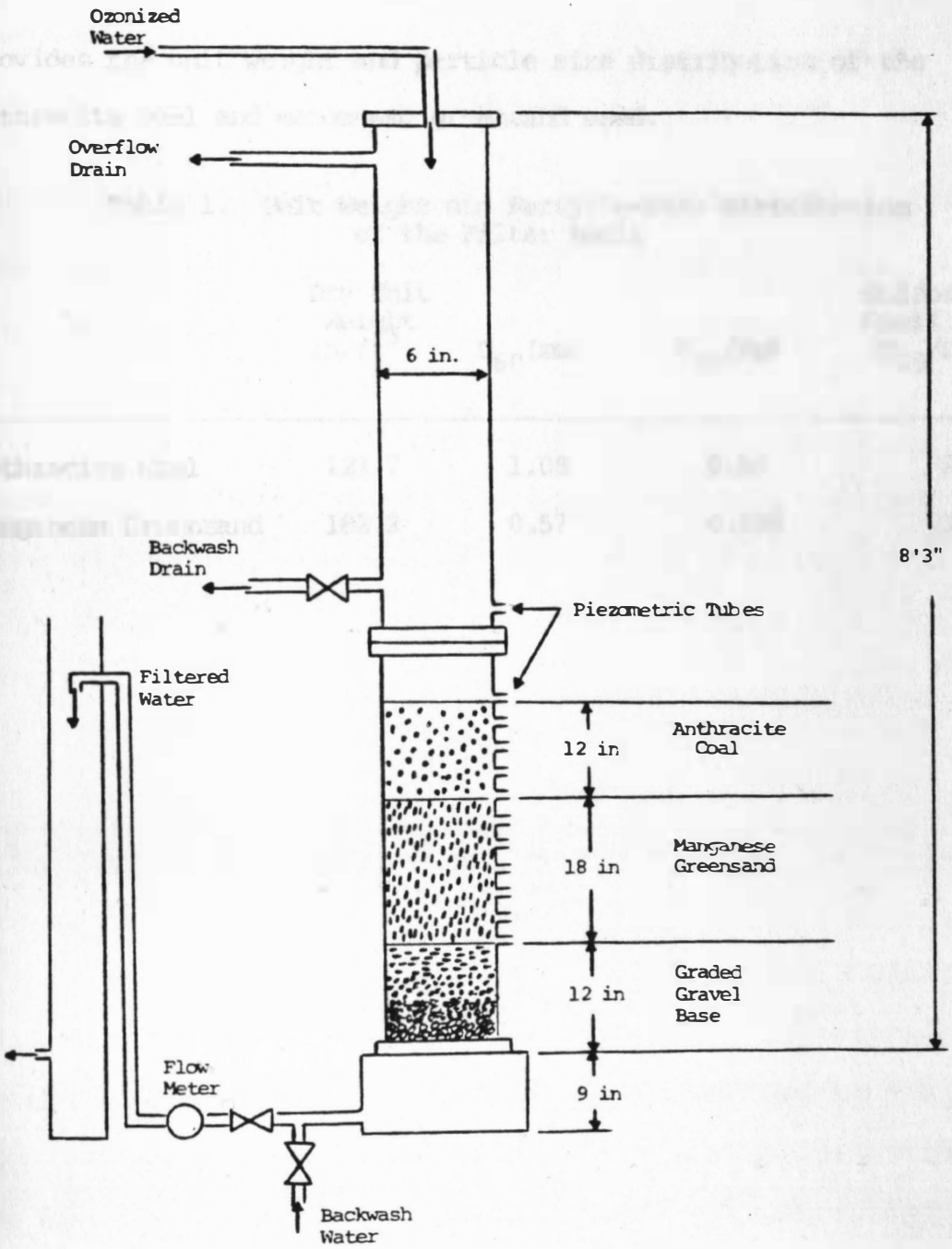

Figure 14. Schematic View of Pilot Filter

provides the unit weight and particle size distribution of the anthracite coal and manganese greensand used.

Table 1. Unit Weight and Particle-Size Distribution of the Filter Media

	Dry Unit Weight lb/ft^3	D_{60} (mm)	D_{10} (mm)	Uniformity Coefficient (D_{60}/D_{10})
Anthracite Coal	121.7	1.08	0.90	1.20
Manganese Greensand	182.2	0.57	0.295	1.93

Operational and Analytical Procedures

Ozone System

The ozone system procedures were operated and performed in the same manner as Stoebner (1) and Schjodt (2). To avoid repetition, this section will provide a brief synopsis for the conditions and procedures used.

Dryness and flow rate of the feed gas, the temperature and pressure in the ozone generator, and the frequency and voltage of the power supply are all factors that determine ozone production. All of these parameters were held constant except voltage. Their values were:

feed-gas flow-rate	0.33 cfm (9.3 lpm)
generator temperature	50^{o}F (10^{o}C)
generator pressure	15 psig (100 kPa)
frequency	60 Hz

In this manner voltage becomes the only control for ozone production. A trial and error process of voltage adjustment was used until the desired ozone concentration was measured leaving the generator. An applied ozone dosage of 4 mg/l was held constant throughout the experiment requiring only small adjustments of the voltage regulator depending on the change in barometric pressure and water contact time.

The method used for determining the ozone concentration in the gas is a variation of the idometric method for measuring ozone residual as described in Standard Methods (16). In brief, a 4 liter

portion of supply gas was passed through a series of two gas washing bottles, each containing 400 ml of one per cent potassium iodide (KI) solution. A wet-test meter was used to measure the volume of gas. When passing the gas through the bottles, ozone is tied up with the KI solution changing it from a clear to a yellow iodine solution (see Figure 15). Subsequent fixing with 2N sulfuric acid (H_2SO_4) and titration with 0.10 N sodium thiosulfate ($Na_2S_2O_3$) using a starch indicator yielded the weight of ozone in the solution. Determining the ozone weight per air volume with a selected air flow rate and water flow rate yields the applied ozone dosage. A description of all the experimental calculations is provided in Appendix A.

Three different detention times were used in this study; 10, 5 and 2.5 minutes. All other parameters were held constant. A constantly applied ozone dosage of 4 mg/l, determined to be the optimum dosage by Stoebner (1), was maintained. Liquid depth in the contact column was kept at 14.5 feet (4.4 m) allowing a constant liquid volume of 21.3 gallons (161 liters) and making the contact time a function of only influent flow rate.

Ozone off-gas is the portion of ozone not utilized by the water and is vented out the top of the column. By keeping the air flow rate constant and performing the previously mentioned gas washing test method on the off-gas, one can determine the amount of ozone lost and hence the transfer efficiency.

Ozone residual in the treated water was determined by a back titration method using a Fischer and Porter Series 17T2000

amperometric titrator (refer to Figure 16). Back titration provided a more distinct "end point" (meter deflection). The method is described in the amperometric titrator instruction bulletin (17). In short, a 200 ml water sample was collected from the contact column effluent and conditioned with a pH 4 buffer and a 5% KI solution. A sufficient known amount of phenylarsene oxide (PAO) was added to the sample and then titrated with an iodine solution of known strength. A description of the experimental calculations is provided in Appendix A.

Filter System

The Inversand Manganese Greensand Company provides suggested operating criteria for the contact bed as listed by Kirschenman (3). A backwash rate sufficient enough to produce approximately a 40% bed expansion is suggested. In an attempt to achieve this expansion the dual media became intermixed. The media was removed and new media was installed. Conditioned anthracite coal was taken from the operating water treatment plant filter beds. Media placement was installed as suggested by Kirschenman (3); First, a graded gravel base of 12-inches (30.48-cm) was installed. Next, 18-inches (45.72-cm) of manganese greensand were placed above the gravel base and a backwash performed. About one inch of bed expansion including migrated fines was removed from the top of the bed. Finally 12-inches (30.48-cm) of conditioned coal were used to cap the greensand. To avoid the intermixing problem, a backwash producing approximately 20% bed expansion was used throughout the study. It is believed that the pilot filter area is

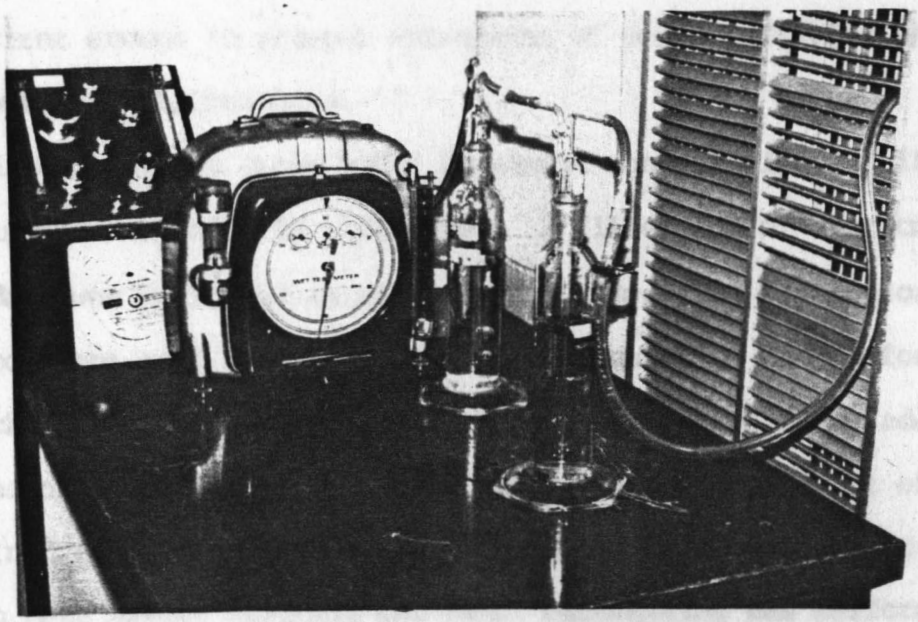

Figure 15. Gas Washing System Used for Collecting Ozone Gas

Figure 16. Back Titration Method for Determining Ozone Residual Concentrations

not sufficient enough to prevent entrapment of media particles when settling out after backwashing.

Three different ozone water treatment contact times of 10, 5 and 2.5 minutes were used in this study. A filter run of four consecutive days was performed at each contact time. The filtration rate was held constant at 2 gpm/ft^2. Complete regeneration was performed before each of the three runs. Regeneration was performed by adding batch doses of potassium permanganate ($KMnO_4$) until the filter effluent turned pink. The filter was then rinsed for 0.5 hours at the filtration rate before starting the run. Backwashing was performed about every 12 hours on the first filter run which was at the 10 minute contact time. It was later realized that the backwashing could be delayed longer to every 24 hours, therefore, backwashing occurred once a day in the second and third filter runs. The time for each backwash was approximately 15 minutes.

Sampling

Samples for total and soluble iron and manganese were collected at the 10 sampling points depicted in Figure 17. Five separate sets of samples were collected for each of the three filter runs. Each set of samples were collected every 24 hours immediately prior to backwashing except for the initial set which was collected 0.5 hours after start-up.

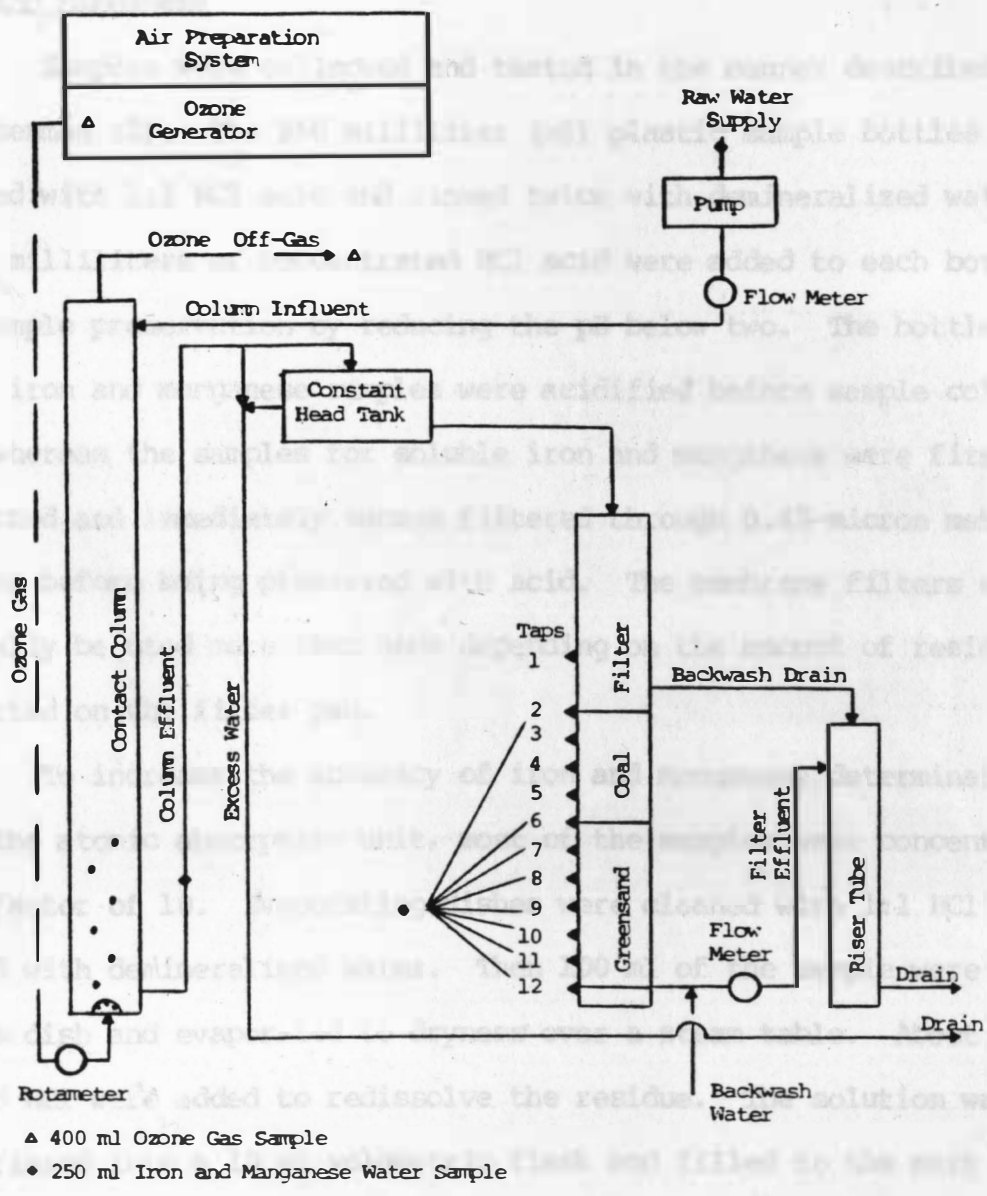

Figure 17. Sampling Locations for Both Ozone Gas and Iron and Manganese Concentrations

Iron and Manganese

Samples were collected and tested in the manner described by Kirscherman (3). The 250 milliliter (ml) plastic sample bottles were cleaned with 1:1 HCl acid and rinsed twice with demineralized water. Three milliliters of concentrated HCl acid were added to each bottle for sample preservation by reducing the pH below two. The bottles for total iron and manganese samples were acidified before sample collection whereas the samples for soluble iron and manganese were first collected and immediately vacuum filtered through 0.45-micron membrane filters before being preserved with acid. The membrane filters could generally be used more than once depending on the amount of residue collected on the filter pad.

To increase the accuracy of iron and manganese determinations with the atomic absorption unit, most of the samples were concentrated by a factor of 10. Evaporating dishes were cleaned with 1:1 HCl and rinsed with demineralized water. Then 100 ml of the sample were added to the dish and evaporated to dryness over a steam table. About 2 ml of 1:5 HCl were added to redissolve the residue. The solution was then rinsed into a 10 ml volumetric flask and filled to the mark with demineralized water prior to analysis.

The Perkin-Elmer Model 2380 atomic absorption spectrophotometer from the Chemistry Department of South Dakota State University was used for iron and manganese determinations (Figure 18). The unit provided statistical digital readout such as relative average absorbance, standard deviation and coefficient of varience. The

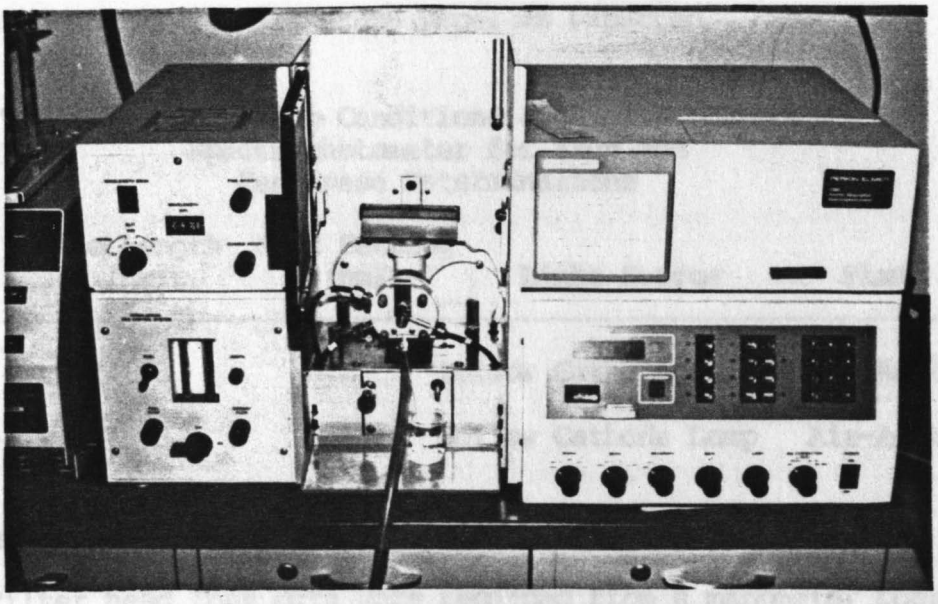

Figure 18. Perkin-Elmer Model 2380 Atomic Absorption Spectrophotometer

samples were aspirated individually by hand. The operating conditions for the atomic absorption unit are summarized in Table 2.

Iron and manganese standards with concentrations ranging from 0.0 to 10.0 mg/l were made from dilutions of stock solutions. The relationship between metal concentration and relative absorbance was linear on rectangular-scale graph paper as expected.

Table 2. Operating Conditions of Atomic Absorption Spectrophotometer for Iron and Manganese Determinations

Metal	Wave Length (nm)	Slot Setting (nm)	Light Source	Flame Type
Iron	248.3	0.2	Hollow Cathode Lamp	Air-Acetylene
Manganese	279.5	0.2	Hollow Cathode Lamp	Air-Acetylene

Filter Head loss

Filter head loss data were recorded from a manometer board before each sampling event. Each tap has a manometer and the difference in water level between each manometer represents the head loss for that particular 3-inch (7.6-cm) section of filter media. The difference in elevation between the water level for sample tap 1 and the effluent riser represented the total head loss through the filter.

RESULTS AND DISCUSSION

Ozone Demand

The applied ozone dosage of 4 mg/l consistently used throughout this study was determined to be the optimum dosage for the Brookings municipal groundwater supply by Stoebner (1). The ozone reaction equations stated in the literature review stoicheometrically indicate that 0.43 mg/l ozone reacts with one mg/l iron, and 0.897 mg/l ozone reacts with one mg/l manganese under near neutral conditions. Considering an overall average iron concentration of 4.51 mg/l and manganese concentration of 0.77 mg/l in the raw water supply, the ozone requirement would be 1.94 mg/l for iron and 0.67 mg/l for manganese for a total ozone requirement of 2.61 mg/l.

Other constituents in the water, such as sulfides and organics exert an additional ozone demand. The organic content in the groundwater is considered small indicating that some excess ozone is needed to force the reactions to completion under normal conditions.

Transfer Efficiency and Ozone Residual

Tabulated values for transfer efficiency and ozone residual can be found in Appendix B. A comparison of transfer efficiency and ozone residual for the three ozone pilot systems is illustrated in Figures 19 and 20 respectively.

Pieterick and Stoebner (1) show an increase in transfer efficiency with decrease in contact time. This trend can be expected due to the continuous ozone demand exerted by increased rates of raw

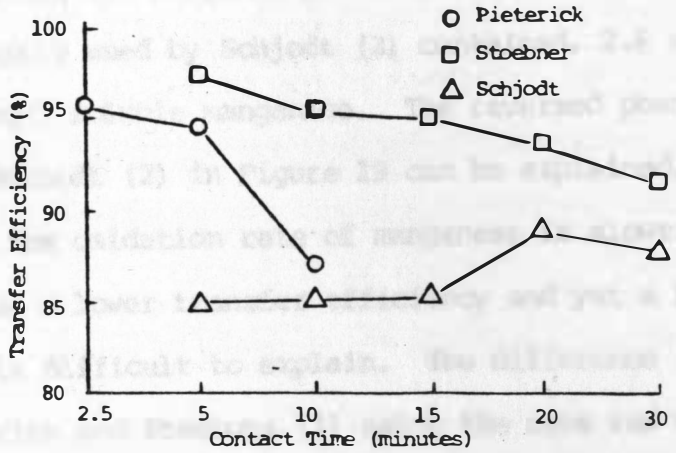

Figure 19. Transfer Efficiency Versus Contact Time at an Applied Ozone Dosage of 4 mg/l

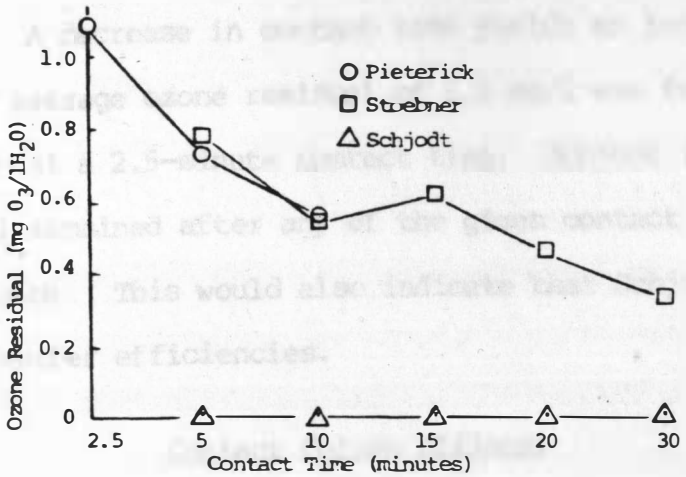

Figure 20. Ozone Residual Versus Contact Time at an Applied Ozone Dosage of 4 mg/l

water constituents via decrease in contact time. The Sioux Falls raw groundwater supply used by Schjodt (2) contained, 2.6 mg/l soluble iron and 2.3 mg/l soluble manganese. The reversed phenomenon illustrated by Schjodt (2) in Figure 19 can be explained, in part, by the fact that the oxidation rate of manganese is slower than iron. Schjodt (2) had a lower transfer efficiency and yet a higher ozone demand; this is difficult to explain. The difference in efficiency between Pieterick and Stoebner (1) using the same raw water supply might be due to the differences in contactors. Stoebner used 2 columns whereas only one column was used in the studies described herein. A lack of efficiency in the ozone generator to manufacture a constant dosage of ozone or fluctuations in raw water constituents may be the explanations.

Figure 20 illustrates a good correlation between Pieterick and Stoebner (1). A decrease in contact time yields an increase in ozone residual. An average ozone residual of 1.1 mg/l was found leaving the contact column at a 2.5-minute contact time. Schjodt (2) found no ozone residual remained after any of the given contact times at a 4 mg/l ozone dosage. This would also indicate that Schjodt should have had higher transfer efficiencies.

Contact Column Effluent

Iron and manganese data determined at different contact times for an applied ozone dosage of 4 mg/l are tabulated in Appendix C. Appendix D contains the statistical analyses. Tables D1 and D2 show that the soluble iron and manganese concentrations in the raw water

did not significantly differ with contact time at the 95% and 99% confidence levels. Tables D3 and D4 show that the soluble iron and manganese concentrations in the contact column effluent did not significantly differ with contact time at the 95% and 99% confidence levels. Therefore, the reduction in contact time from 10 minutes to 2.5 minutes is not significant in the reduction of soluble iron and manganese.

Figures 21 and 22 respectively illustrate the soluble iron and manganese concentrations determined at the different contact times for the three ozone pilot systems. At a 4 mg/l ozone dosage and all the given contact times, the pilot systems were capable of reducing the soluble iron concentrations to below the 0.3 mg/l USPHS standard. Iron concentrations determined by Pieterick were more erratic ranging from 0.0 mg/l to 0.45 mg/l for the 2.5-minute and 5-minute contact time runs (refer to Table C1). Figure 21 clearly illustrates the poorer soluble iron removal efficiency of the Pieterick ozone pilot system at the 4 mg/l ozone dosage. All three systems show little if any trend in soluble iron reduction with contact time.

Pieterick and Stoebner (1) correlate relatively well for soluble manganese concentrations leaving the contact column as indicated by Figure 22. With the exception of an outcrop at the 10 minute contact time for Schjodt (2), all three systems show an increase in soluble manganese with decrease in contact time. Statistics show the trends to be insignificant, but the trend of Pieterick shows a sharp increase in soluble manganese as contact time is reduced to less than

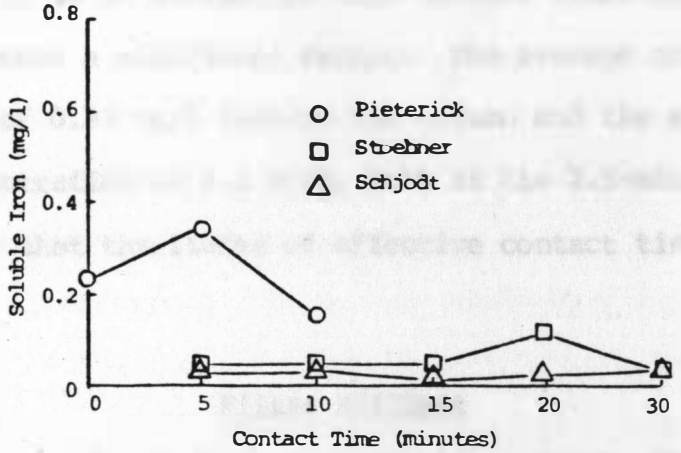

Figure 21. Soluble Iron in Contact Column Effluent at Different Contact Times

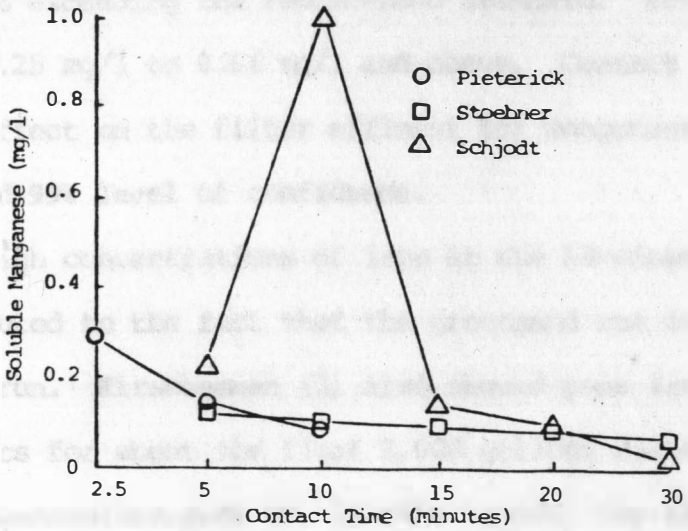

Figure 22. Soluble Manganese in Contact Column Effluent at Different Contact Times

5 minutes. This is an indication that contact times below five minutes may become a signficant factor. The average soluble manganese concentration of 0.29 mg/l leaving the column and the average ozone residual concentration of 1.1 mg/l, both at the 2.5-minute contact time, indicate that the limits of effective contact time may have been reached.

Filter Effluent

The iron and manganese concentrations in the filter effluent are tabulated in Appendix C. Tables D5 and D6 show an analysis of variance on the total iron and manganese leaving the filter respectively. Statistics show the filter effluent for iron to be significantly different at different contact times at the 95% and 99% level of confidence. The 10-minute contact time showed the highest concentrations exceeding the recommended standard. Concentrations ranged from 0.25 mg/l to 0.64 mg/l and above. Contact time had no significant effect on the filter effluent for manganese concentrations at the 95% and 99% level of confidence.

The high concentrations of iron at the 10-minute contact time may be attributed to the fact that the greensand was not fully ripened in the first run. Kirscherman (3) also showed poor iron removal characteristics for about the first 2,000 gallons filtered in the intermittent regeneration mode or, in other words, the aeration, detention, and filtration scheme. Both systems had acceptable manganese concentrations in the filter effluent to start with.

Manganese concentrations occasionally exceeded the 0.05 mg/l recommended limit. Slightly higher concentrations occurred in the first samples collected for each run which were collected 30 minutes after $KMnO_4$ regeneration. Some residual $KMnO_4$ may have been present in the samples collected initially.

The most economical contact time would be 2.5 minutes. Figures 23 and 24 respectively show the plotted iron and manganese values recorded for four consecutive days at the 2.5-minute contact time. With the exception of one total iron concentration, both the iron and manganese concentrations in the filter effluent fall within recommended limits. Unlike the coal filter used by Stoebner (1) and Schjodt (2), there were no signs of iron or manganese breakthrough in the dual media filter effluent prior to backwashing necessitated by head loss build-up. Therefore, in this sytem, head loss is the controlling factor, not filter breakthrough, in determining the duration of filter runs.

Filter Performance

Table C1 and Table C2 respectively show iron data and manganese data collected throughout the filter media. The mean reduction in soluble iron from 0.22 mg/l at the contact column effluent to 0.15 mg/l at the filter coal surface can be attributed to added detention with the ozone residual providing further oxidation. Soluble manganese showed no reduction between these two locations.

The coal media was only capable of removing about one third (4.51 mg/l to 3.13 mg/l) of the insoluble iron floc. The insoluble

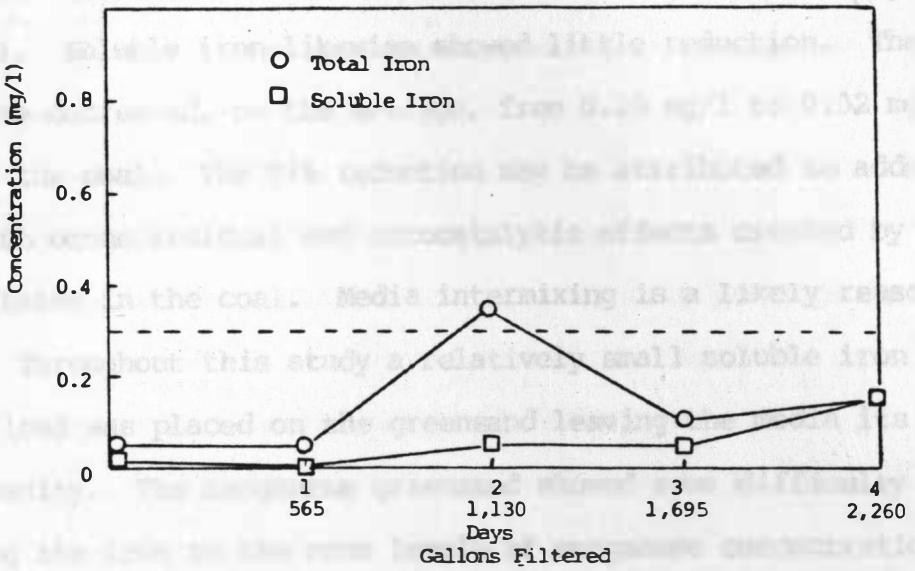

Figure 23. Iron Concentrations in Filter Effluent Versus Time or Gallons for 2.5 Minute Contact Time - Pieterick

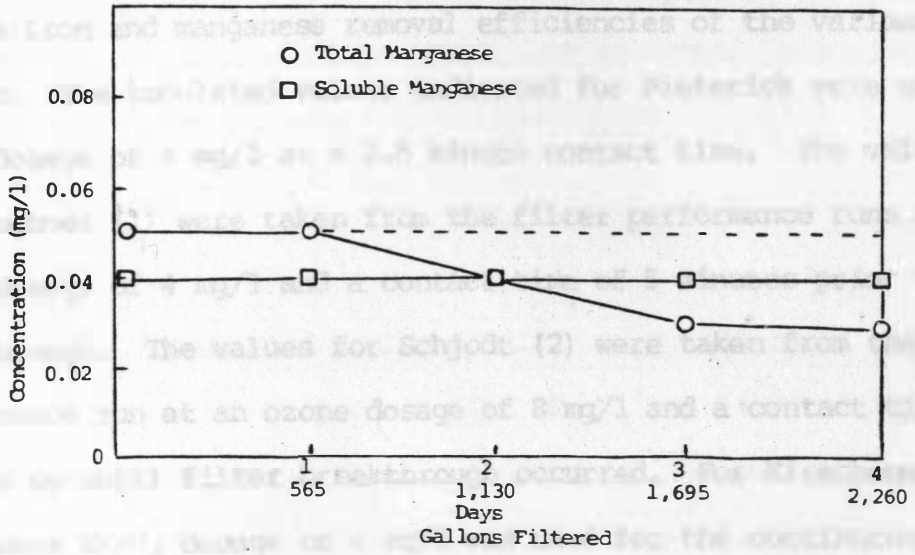

Figure 24. Manganese Concentrations in Filter Effluent Versus Time or Gallons for 2.5 Minute Contact Time - Pieterick

manganese values are erratic showing little signs of reduction through the coal. Soluble iron likewise showed little reduction. The soluble manganese decreased, on the average, from 0.29 mg/l to 0.02 mg/l through the coal. The 93% reduction may be attributed to added detention with ozone residual and autocatalytic effects created by MnO_2 precipitates in the coal. Media intermixing is a likely reason.

Throughout this study a relatively small soluble iron and manganese load was placed on the greensand leaving the media its oxidizing capacity. The manganese greensand showed some difficulty in reducing the iron to the same levels of manganese concentrations, but overall, the greensand was capable of removing 93% of the ozonized iron and manganese floc.

Removal Efficiencies

Table E1 and Table E2 of Appendix E, respectively compare the average iron and manganese removal efficiencies of the various pilot systems. The tabulated values indicated for Pieterick were using an ozone dosage of 4 mg/l at a 2.5 minute contact time. The values used for Stoebner (1) were taken from the filter performance runs at an ozone dosage of 4 mg/l and a contact time of 5 minutes prior to filter breakthrough. The values for Schjodt (2) were taken from the filter performance run at an ozone dosage of 8 mg/l and a contact time of 5 minutes up until filter breakthrough occurred. For Kirschenman, a continuous $KMnO_4$ dosage of 4 mg/l was used for the continuous mode. For the intermittent mode, the values used were up until contact bed mid-depth breakthrough of manganese occurred.

Under these conditions all of the pilot systems were capable of reducing iron and manganese by at least 93.7% to within recommended limits. These values indicate typical removal efficiencies under optimum or design conditions. Table E1 notes that Kirschenman (3) oxidized 96.6% of the soluble iron by aeration and removed 48.8% of the insoluble iron floc in the 2.3 hour detention basin before filtration in the intermittent regeneration mode. Over 96% of soluble iron for all the systems were oxidized before filtration.

Excluding Kirschenman's (3) intermittent mode, no soluble manganese load was placed on the greensand. Soluble manganese was reduced anywhere from 7.4% to 26.8% through the coal media. Most of the reduction has been attributed to ozone residual and slow autocatalytic effects. The 18.6% soluble manganese reduction through the coal media in the aeration detention scheme used by Kirschenman indicates that coal may have some oxidizing capabilities. The author believes however a considerable amount of greensand intermixed with the coal during backwash operations biasing the results.

Filter Head Loss

Tabulated values for head loss at 0.5, 12 and 24 hours since backwashing are presented in Appendix F. Figure 25 shows total head loss development with respect to time or gallons filtered for the various pilot systems. Figure 26 illustrates the incremental head loss developed after 24 hours through the filter media for the various pilot systems. All of the systems used a filter rate of 2 gpm/ft^2.

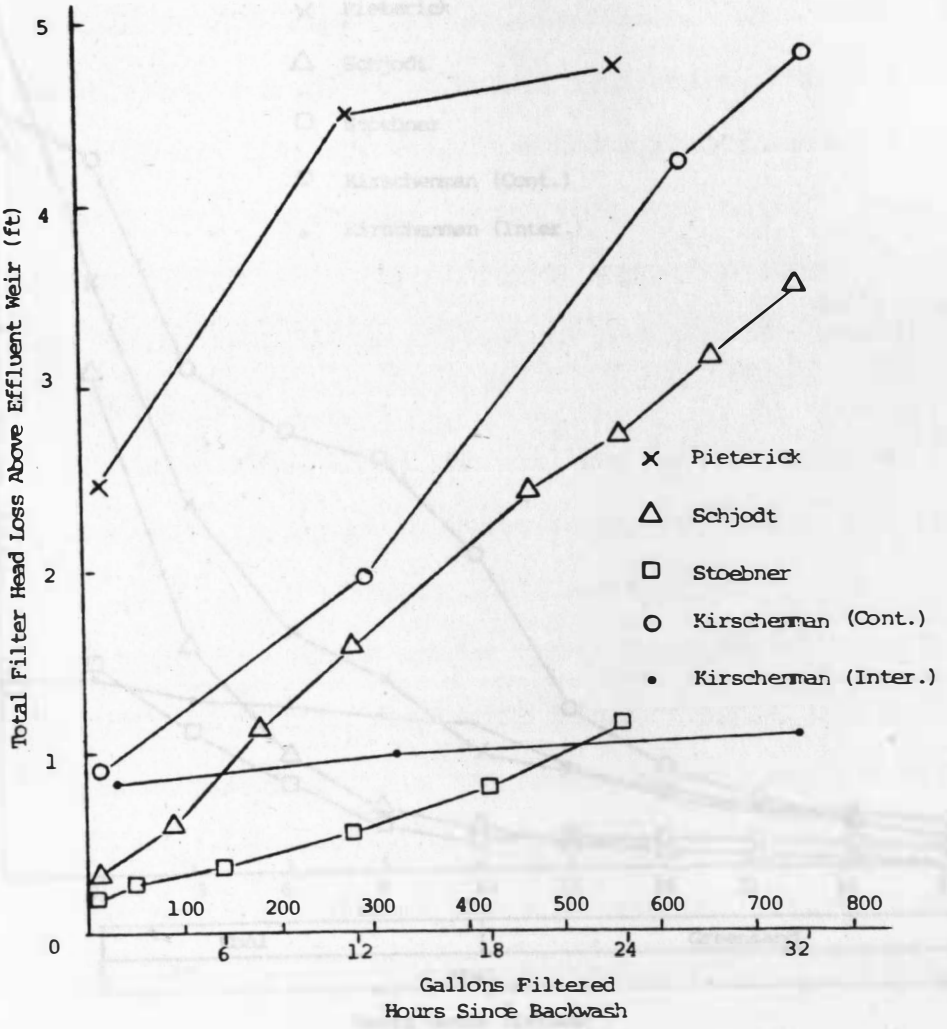

Figure 25. Total Filter Head Loss Versus Time or Gallons

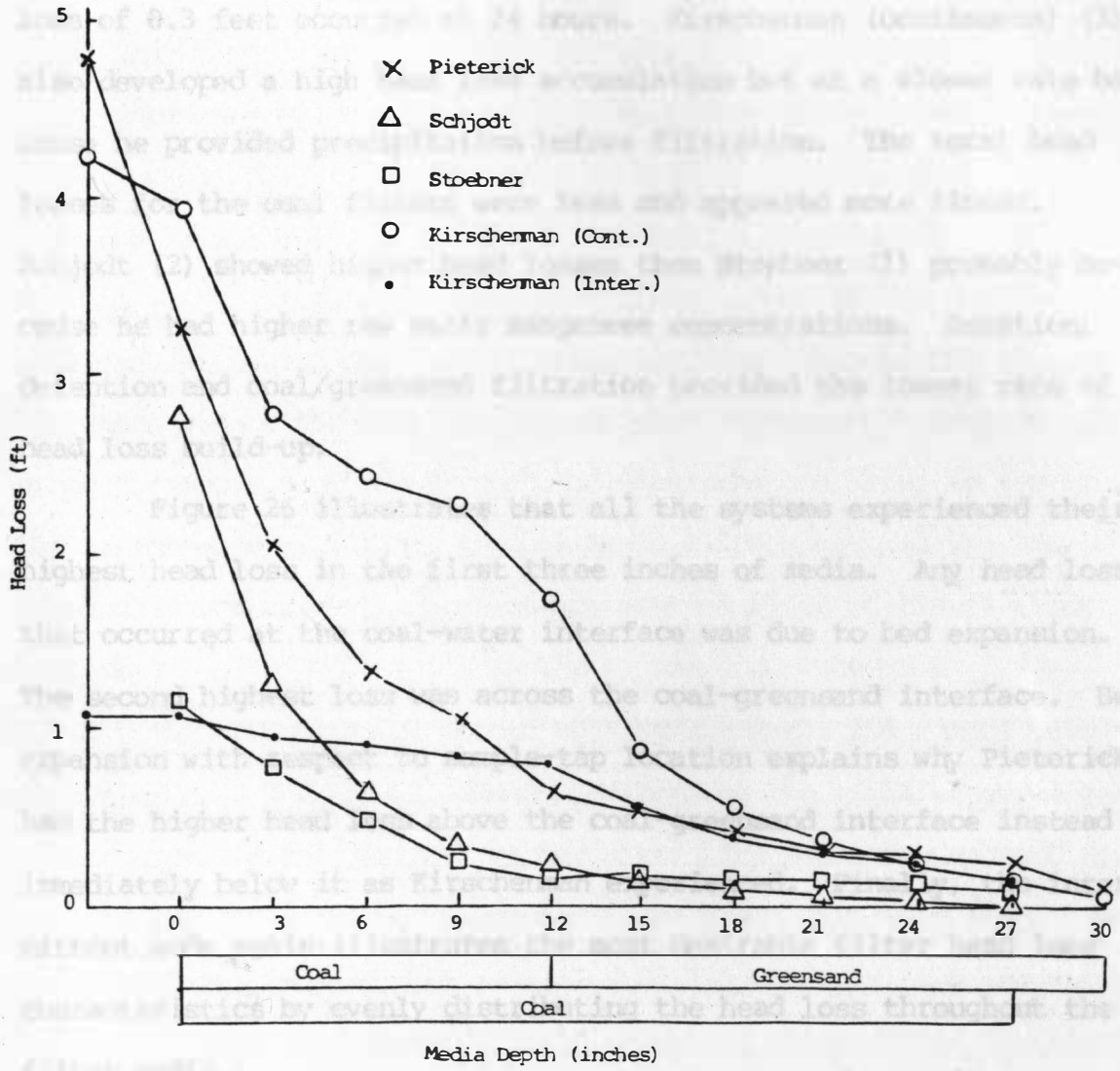

Figure 26. Head Loss Through Filter Medium 24 Hours Since Backwash

Pieterick experienced the highest rate of total head loss accumulation reaching 4.5 feet in 12 hours; only an additional head loss of 0.3 feet occurred at 24 hours. Kirschenman (continuous) (3) also developed a high head loss accumulation but at a slower rate because he provided precipitation before filtration. The total head losses for the coal filters were less and appeared more linear. Schjodt (2) showed higher head losses than Stoebner (1) probably because he had higher raw water manganese concentrations. Aeration, detention and coal/greensand filtration provided the lowest rate of head loss build-up.

Figure 26 illustrates that all the systems experienced their highest head loss in the first three inches of media. Any head loss that occurred at the coal-water interface was due to bed expansion. The second highest loss was across the coal-greensand interface. Bed expansion with respect to sample-tap location explains why Pieterick had the higher head loss above the coal-greensand interface instead of immediately below it as Kirschenman experienced. Finally, the intermittent mode again illustrates the most desirable filter head loss characteristics by evenly distributing the head loss throughout the filter media.

It is estimated that about 10 to 12 feet of filter freebroad would be needed to permit filter runs of three or four days between backwashes for the manganese greensand at a 2 gpm/ft^2 filter rate. Stoebner (1) and Schjodt (2) determined the longest practical run for a coal filter would be 10 hours and 20 hours, respectively, based on

filter breakthrough. This would generate higher backwash frequencies and large volumes of backwash water.

Cost Analysis

An analysis was performed to determine if the conversion of the Brookings East Water Treatment Facility from a chemical treatment plant to an ozone/greensand system would be cost effective over the next 20 years. Figure G1 provides a flow diagram of the east water treatment plant. Comparison of costs involved the construction and operation and maintenance of an ozone generation system including a contact chamber, and the purchase of greensand and labor to convert the exisiting coal filters to dual media filters against the projected chemical costs using the present application rates of the existing facility.

The optimum ozone dosage of 4 mg/l and the 2.5 minute detention time were the values used in determining the required ozone generator capacity and contact chamber size. The projected average flow for the next 20 years was estimated to be 3 MGD (11,350 m^3/day) given the 1984 total treated flow of 1.85 MGD (7,000 m^3/day) and the existing plant capacity of 4 MGD (15,200 m^3/day). Calculations in Appendix G show an ozone generation capacity of 100 lb/day (45.5 kg/day) and a contact chamber volume of 696.3 ft^3 (19.7 m^3) are required.

Cost curves developed by the United States Environmental Protection Agency (EPA) were used for estimating the cost of installing and operating an ozonation process (18). The use of air as a feed gas for the 100 lb/day ozone generator was considered in the EPA cost

data. The manufactured equipment for ozone generation included the gas preparation equipment, ozone generator, dissolution equipment, off-gas recycling equipment, instrumentation and controls, and safety and monitoring devices. All ozone generation equipment was considered to be housed, however in this case housing is provided. Therefore, the portion of labor cost involved with housing was assumed to be the cost of materials and labor needed for constructing partitions in the existing recarbonation basin for the required contact chamber volume. A 10 per cent allowance was added to the construction cost for miscellaneous items and contingencies.

EPA assumed that the process energy involved for ozone generation using air feed would be about 11 kw-hr/lb of O_3 (24 kw-hr/kg of O_3). To determine the annual energy cost, a 20 year average unit price of $0.07/kw-hr was assumed. Labor requirements for periodic maintenance of the generating equipment were converted to annual cost using a labor rate of $12/hr. Based on manufacturer's recommendations, annual maintenance material expense is roughly 1 per cent of construction cost.

The EPA cost curves used were based on October 1978 prices. Cost indices published by Engineering News Record (19) and by the Bureau of Labor Statistics (20) were used for updating the costs as illustrated in Table G1. The total cost of constructing the ozone system is $299,360 and the annual cost of operation and maintenance is $39,150/yr as computed in Table G2.

As shown in Table G3, converting the coal filters to coal/greensand filters will cost approximately $74,060. This cost includes: removing the coal including the top 3 inches (7.6 cm) of support gravel, replacing the removed gravel, adding 18 inches (46 cm) of greensand, and capping the filter bed with 12 inches (30 cm) of the existing anthracite coal. No provisions for an air wash system were considered needed. The cost of providing additional filter freeboard was also not included. Increasing an assumed 8 feet (2.4 meters) of available head loss to 12 feet (3.6 m) would involve about 10 cubic yards (7.6 m^3) of concrete with rebar. A 40 per cent labor and contingency cost is included.

Table G4 shows the 1984 chemical feed rates used and the 1984 unit costs paid for the Brookings lime softening plant. Using a projected 20 year average flow of 3 MGD and a projected average inflation factor of 25 per cent the annual average cost of chemicals is $71,130/yr.

The following cost analysis presented in Table 3 illustrates the feasibility of converting the east water treatment plant to an ozone/greensand facility. The total construction cost of $373,420 was amortized over a 20-year period for the various interest rates. The total annuity including the annual cost of operation and maintenance for the ozone system is then compared to the projected annual cost for chemicals for the existing plant. According to Table 3 the conversion becomes cost effective at about 5.5% rate of interest (6.5 cents per 1000 gallons treated). Since this interest rate is

currently unattainable, this conversion would not be feasible. However it should be pointed out that annual operation and maintenance costs for the aerator, chemical feed equipment and upflow basin were not incorporated in this analysis. Also any possible reduction in chlorine demand due to ozonation was not considered. The inclusion of this information could raise the effective rate of interest to current levels but the author believes the annual gain would not be enough to offset possible contingency.

Table 3 Treatment Cost Comparison Analysis

Interest Rate (%)	Capital Recovery Factor	Annual Cost of Construction (dollars)	Total Annuity (dollars)	Annual Cost of Chemicals (dollars)	Annual Gain or Loss (dollars)
5	0.08024	29,960	69,110	71,130	+2,020
6	0.08718	32,550	71,700	71,130	- 570
7	0.09439	35,250	74,400	71,130	-3,270
8	0.10185	38,030	77,180	71,130	-6,050

Note: Total construction cost = $299,360 + 74,060 = $373,420

Annual operation and maintenance cost = $39,150

All calculations were based upon a 3 MGD flow, 2.5 minute contact time, and 4 mg/l ozone dosage

Projection and repayment based on 20 years starting 1985.

CONCLUSIONS

Based upon the investigations described herein, the following conclusions are made:

1. Ozone transfer efficiency appears to increase with decrease in contact time at an applied ozone dosage of 4 mg/l.
2. Ozone residual in the contact column effluent increases with decrease in contact time at an applied ozone dosage of 4 mg/l.
3. A reduction in contact time from 10 minutes to 2.5 minutes did not significantly change the soluble iron and manganese concentration in the contact column effluent at an applied ozone dosage of 4 mg/l.
4. Soluble iron was reduced by 96.7% and soluble manganese was reduced by 72.0% in the contact column using a contact time of 2.5 minutes at an applied ozone dosage of 4 mg/l.
5. Manganese greensand effectively removed total iron and manganese floc to within USPHS drinking water standards.
6. Unlike the coal filter used by Stoebner (1) and Schjodt (2), there were no signs of iron and manganese "breakthrough" in the greensand filter effluent.
7. Relatively little soluble iron or manganese load was placed on the greensand leaving the media its oxidizing capacity.
8. Within recommended filter runs, all of the pilot systems were capable of reducing iron and manganese by at least 93.7% to within recommended limits making ozone no more effective than potassium permanganate under the given conditions.

9. The greensand filters produced the most rapid increase in head loss, up to 4.8 feet in 24 hours in this study.
10. Regardless of the filter media, the head loss accumulation through the filters was nonlinear with respect to media depth with the largest amount of head loss occurring through the coal.
11. Based on prices ending the 1984 year, conversion of the Brookings East Water Treatment Facility from a chemical treatment plant to an ozone/greensand system would become cost effective at a currently unattainable interest rate of 5.5%.

RECOMMENDATIONS FOR FUTURE STUDIES

The following recommendations are made for future studies involving the ozone pilot plant.

1. Contact times below 2.5 minutes should be investigated. This can be accomplished by removing a section of the contact column to reduce its volume.
2. The constant-head tank should be covered to avoid stripping ozone when using very short contact times with high ozone residuals. This will preserve ozone for obtaining additional reductions of soluble iron and manganese and reduce ozone levels in the areas near the pilot system that might otherwise cause irritation to eyes and throat membranes.
3. A larger diameter pilot filter should be constructed to prevent particle intermixing and entrapment as a result of backwashing.
4. The height of the pilot filter should be increased to provide more head loss so that a better estimate of the practical length of filter runs can be made.

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APPENDIX A

EXPERIMENTAL CALCULATIONS

OZONE PILOT PLANT PERFORMANCE DATA

GENERAL INFORMATION

Date _____ Run Number _____

Approximate Ozone Dosage _____ mg/l

Detention Time _____ min

Barometric Pressure _____ in Hg x 13.6 = _____ in H_2O

x .4912= _____ psi

OZONE GENERATOR

Number of Tubes _____ Percent Voltage _____ %

Generator Pressure _____ psi Volts _____

OZONIZED GAS FLOW RATE

Rotameter Flow Rates: Maximum Flow Rate = 1.1 cfm

Contactor #1 30 % of max flow = .33 cfm

Contactor #2 - % of max flow = - cfm

P_1 = Adjusted Pressure = Gauge Backpressure (_____psig) +

Barometric Pressure (_____psi) = _____psia

P_2 = Standardizing Gauge Pressure + Standard Pressure = 14.7 psia

C_p = Pressure Correction Factor $\sqrt{\frac{P_1}{P_2}}$ = _____

T_1 = Ozonized Air Temperature = _____ ^oF = 459.6^o = _____ ^oR

T_2 = Standardizing Gauge Temperature = 70^oF + 459.6^o = 529.6^oR

T_3 = Standard Temperature = 77^oF + 459.6^o = 536.6^oR

C_t = Temperature Correction Factor = $\sqrt{\frac{T_2}{T_1}} \left(\frac{T_3}{T_2}\right)$ = _____

Corrected Flow Rate = (Flow Rate) $(C_p)(C_t)$

Contactor #1 _____ cfm

Contactor #2 _____ cfm

Total _____ cfm

OZONE CONCENTRATION IN SUPPLY GAS

Wet Test Meter: Final Reading _____

- Initial Reading _____

V_1 = Gas Volume = 4 liters

T_1 = Meter Temperature = _____ $^oC \times \frac{9}{5} + 32 + 459.6 =$ _____ ^oR

T_2 = Standard Temperature = $77^oF + 459.6^o = 536.6^oR$

C_t = Temperature Correction Factor = T_2/T_1 = _____

P_b = Barometric Pressure _____ in H_2O

P_m = Meter Manometer Deflection _____ in H_2O

P_v = Water Vapor Pressure _____ in H_2O

P_1 = Adjusted Pressure = $P_b + P_m - P_v$ = _____ in H_2O

P_2 = Standard Pressure = 1 atmosphere = 406.8 in H_2O

C_p = Pressure Correction Factor = P_1/P_2 = _____

V_2 = Gas Volume Corrected to STP = $(V_1)(C_t)(C_p)$ = _____ liters

N = Normality of Sodium Thiosulfate Titrant 0.10

Titration: Final Buret Reading _____

- Initial Buret Reading _____

ml titrant = _____

Wt O_3 = (N)(ml titrant)(24) = _____ mg O_3

Ozone Concentration = $\frac{\text{Wt } O_3}{V_2}$ = _____ mg O_3/liter of air

Percent Ozone by Weight = (Ozone Concentration) (0.0843) = _____ Wt %

OZONE PRODUCTION

Ozone Production = Corrected Air Flow Rate (_____ cfm) x Ozone Concentration (____ mg/l) x 0.089944 = _____ lb 0_3/day

APPLIED OZONE DOSAGE

mg 0_3/l H_20 = mg 0_3/l air $(\frac{\text{air flow rate (cfm)}}{\text{water flow rate (cfm)}})$

Total Ozone Dosage _____ mg 0_3/l H_20

Ozone Dosage to Contactor #1 _____ mg 0_3/l H_20

Ozone Dosage to Contactor #2 _____ mg 0_3/l H_20

OZONE CONCENTRATION IN OFFGAS

Wet Test Meter: Final Reading _____

- Initial Reading _____

V_1 = Gas Volume ____4____ liters

V_2 = Gas Volume Corrected to STP = $(V_1)(C_t)(C_p)$ = _____ liters

N = Normality of Sodium Thiosulfate Titrant ____0.10____

Titration: Final Buret Reading _____

- Initial Buret Reading _____

ml of Titrant _____

Wt 0_3 = (N) (ml of titrant) (24) = _____ mg 0_3

Ozone Concentration = $\frac{\text{Wt } 0_3}{V_2}$ = _____ mg 0_3/l of air

OZONE LOSS VIA OFFGAS

Offgas Flow Rate = $(\frac{\text{liters}}{\text{sec}})$ (60) (.0353) = _____ cfm

Corrected Gas Flow Rate = (Offgas Flow Rate) $(C_t)(C_p)$ = _____ cfm

Ozone Loss = Corr. Gas Flow Rate x Ozone Conc. in Offgas x 0.089944

= _____ lb 0_3/day

CONTACTING EFFICIENCY

$$\text{Efficiency} = \left(\frac{\text{Ozone Production}(\quad \text{lb/day}) - \text{Ozone Loss}(\quad \text{lb/day})}{\text{Ozone Production}(\quad \text{lb/day})}\right) 100\%$$

= _____%

ABSORBED OZONE DOSE

Absorbed Dose = (Applied Dosage)(Contacting Efficiency)

= _____ mg 0_3/l H_2O

OZONE RESIDUAL

Sample Volume = 200 ml H_2O

Normality of PAO Titrant = 0.00564

Amperometric Titrator: (Back Titration)

'K' Factor of Iodine = _____

Ozone Residual = (10 ml PAO Added - K x ml Iodine) x 0.677

= _____ mg 0_3/l H_2O

OZONE DEMAND

Ozone Demand = Absorbed Ozone Dose - Ozone Residual _____ mg 0_3/l H_2O

APPENDIX B

TRANSFER EFFICIENCY AND OZONE RESIDUAL

Table B1. TRANSFER EFFICIENCY AND OZONE RESIDUAL

Detention Time (minutes)	Efficiency (%)	Ozone Residual (mg/l)
2.5	96.1	1.10
	96.1	1.10
	95.9	1.07
	95.9	1.09
5.0	94.9	0.65
	94.9	0.80
	93.5	0.74
	94.4	0.73
10.0	86.1	0.53
	86.1	0.53
	88.9	0.56
	87.0	0.54

Note: Applied ozone dose at 4 mg/l

APPENDIX C
IRON AND MANGANESE DATA

Table C1. TOTAL AND SOLUBLE IRON DATA USING AN APPLIED OZONE DOSE OF 4 mg/l

Date 1984	Contact Time (min)	Filtrate Volume (gal)	Time Since Backwash (hrs)		Raw Water		Contact Column Effluent		Coal Surface Influent		Coal Greensand Interface		Sample Tap 7		Sample Tap 8		Sample Tap 9		Sample Tap 10		Sample Tap 11		Contact Bed Effluent	
					T	S	T	S	T	S	T	S	T	S	T	S	T	S	T	S	T	S	T	S
3/31		12	0.5		4.0	3.2	6.4	0.07	4.2	0.04	0.45	0.12	0.28	1.0	0.25	0.31	0.34	0.09	0.01	0.15	0.31	0.07	0.64	0.79
4/1		565	9.8		4.5		5.3	0.26			*	0.52	0.56	0.06	0.54	0.07	0.09	0.04	0.15	0.02	0.20	0.15	*	0.94
4/2	10	1,130	9.0		4.3	3.9	6.2	0.10	4.2	0.09	*	0.34	*	0.10	*	0.26	0.12	0.02	0.18	0.06	0.10	0.04	0.43	0.23
4/3		1.695	11.0		4.3	3.7	5.1	0.12	4.3	0.14	*	0.14	*	0.01	3.2	0.14	*	0.02	0.72	0.29	0.23	0.07	0.25	0.17
4/4		2,260	12.3		5.3	4.2	6.2	0.18	4.5	0.10	6.2	0.25	6.7	0.10	2.4	0.06	0.52	0.06	0.42	0.07	0.26	0.06	0.40	0.29
				$\bar{X}$	4.48	3.75	5.84	0.15	4.30	0.09		0.27		0.25		0.17		0.05	0.30	0.12	0.22	0.08		0.48
				$\bar{S}$	0.49	0.42	0.59	0.07	0.14	0.04		0.16		0.42		0.11		0.03	0.28	0.11	0.08	0.04		0.35
5/30		12	0.5		5.0	3.9	4.5	0.00	3.9	0.29	1.2	0.07	0.7	0.07	0.26	0.20	0.47	0.26	0.37	0.45	0.53	0.29	0.12	0.69
5/31		565	22.8		3.9	3.4	4.7	0.45	3.7	0.07	5.6	0.10	4.5	0.04	2.8	0.1	0.10	0.31	0.12	0.15	0.18	0.04	0.04	0.07
6/1	5	1,130	20.6		4.5	3.5	4.0	0.80	4.5	0.30	4.0	0.10	2.0	0.10	2.0	0.10	2.0	0.20	0.65	0.20	0.40	0.04	0.10	0.20
6/2		1,695	20.8		4.0	4.0	5.0	0.20	4.5	0.15	3.0	0.04	8.5	0.04	5.0	0.15	3.0	0.10	0.65	0.10	0.15	0.1	0.04	0.15
6/3		2,260	24.7		4.2	4.2		0.25	4.2	0.13	1.6	0.07	6.5	0.07	5.3	0.13	4.2	0.07	1.2	0.07	0.3	0.13	0.19	0.13
				$\bar{X}$	4.32	3.80	4.55	0.34	4.16	0.19	3.08	0.08	4.44	0.06	3.07	0.14	1.95	0.19	0.60	0.19	0.31	0.12	0.10	0.25
				$\bar{S}$	0.44	0.34	0.42	0.30	0.36	0.10	1.80	0.03	3.19	0.03	2.11	0.04	1.92	0.10	0.40	0.15	0.16	0.10	0.06	0.25
6/5		12	0.5		5.3	4.5	5.3	0.20	5.8	0.24	1.1	0.00	1.0	0.1	0.92	0.10	0.77	0.05	0.30	0.05	0.20	0.05	0.05	0.01
6/6		565	24.6		4.3	3.9	4.3	0.34	5.8	0.20	7.7	0.1	6.8	0.39	3.4	0.05	0.5	0.05	0.30	0.00	0.20	0.00	0.05	0.00
6/7	2.5	1,130	22.7		5.0	5.0	5.5	0.00	4.5	0.10	3.0	0.1	10.5	0.75	5.5	0.05	3.0	0.05	0.97	0.10	0.35	0.05	0.35	0.05
6/8		1,695	25.0		5.1	5.1	4.5	0.16	4.5	0.10	0.62	0.10	0.98	0.05	3.9	0.05	2.2	0.05	0.90	0.05	0.16	0.05	0.10	0.05
6/9		2,260	24.0		4.0	4.0	4.5	0.45	4.5	0.10		0.20	10.5	0.1	5.0	0.15	3.5	0.05	1.25	0.1	0.3	0.1	0.15	0.15
				$\bar{X}$	4.74	4.50	4.82	0.23	5.02	0.15	3.10	0.10	5.96	0.28	3.74	0.08	1.99	0.05	0.74	0.06	0.24	0.05	0.14	0.05
				$\bar{S}$	0.56	0.55	0.54	0.17	0.71	0.07	3.32	0.07	4.78	0.30	1.79	0.04	1.33	0.00	0.43	0.04	0.08	0.03	0.12	0.06
Mean				$\dot{X}$	4.51	4.04	5.11	0.22	4.51	0.15	3.13	0.15	4.58	0.20	2.89	0.13	1.49	0.09	0.55	0.12	0.26	0.08	0.21	0.26
Standard Deviation				$\dot{S}$	0.50	0.55	0.76	0.20	0.60	0.08	2.47	0.13	3.88	0.29	1.91	0.08	1.45	0.09	0.40	0.12	0.11	0.07	0.18	0.30

T - total
S - soluble
* - numbers out of range of curve > 10 ppm

Table C2. TOTAL AND SOLUBLE MANGANESE DATA USING AN APPLIED OZONE DOSE OF 4 mg/l

Date 1984	Contact Time (min)	Filtrate Volume (gal)	Time Since Backwash (hrs)	Raw Water		Contact Column Effluent		Coal Surface Influent		Coal Greensand Interface		Sample Tap 7		Sample Tap 8		Sample Tap 9		Sample Tap 10		Sample Tap 11		Contact Bed Effluent	
				T	S	T	S	T	S	T	S	T	S	T	S	T	S	T	S	T	S	T	S
3/31		12	0.5	0.70	0.57	0.87	0.08	0.58	0.09	0.00	0.04	0.15	0.03	0.31	0.02	0.08	0.08	0.19	0.29	0.06	0.04	0.09	0.08
4/1		565	9.8	0.62		0.74	0.11			0.38	0.01	0.01	0.00	0.03	0.00	0.03	0.02	0.04	0.02	0.05	0.02	0.01	0.05
4/2	10	1,130	9.0	0.70	0.55	0.89	0.07	0.59	0.08	0.72	0.02	0.71	0.00	0.38	0.00	0.02	0.02	0.05	0.01	0.03	0.02	0.01	0.01
4/3		1,695	11.0	0.66	0.60	0.72	0.08	0.60	0.07	4.6	0.03	3.8	0.00	0.45	0.01	0.40	0.00	0.13	0.01	0.04	0.01	0.04	0.01
4/4		2,260	12.3	0.80	0.72	0.75	0.08	0.66	0.08	0.70	0.03	1.0	0.01	0.00	0.00	0.08	0.00	0.06	0.00	0.03	0.01	0.05	0.01
				$\bar{X}$ 0.70	0.61	0.79	0.08	0.61	0.08	1.28	0.03	1.13	0.01	0.23	0.01	0.12	0.02	0.09	0.07	0.04	0.02	0.04	0.03
				S 0.07	0.08	0.08	0.01	0.04	0.01	1.88	0.01	1.54	0.01	0.21	0.01	0.16	0.03	0.06	0.12	0.01	0.01	0.03	0.03
5/30		12	0.5	0.70	0.50	0.30	0.13	0.50	0.10	0.18	0.01	0.10	0.01	0.04	0.02	0.09	0.01	0.04	0.01	0.05	0.01	0.08	0.07
5/31		565	22.8	0.50	0.60	0.50	0.15	0.50	0.10	0.50	0.00	0.45	0.00	0.30	0.00	0.04	0.01	0.02	0.01	0.02	0.01	0.04	0.03
6/1	5	1,130	20.6	0.80	0.80	0.40	0.15	0.50	0.17	0.60	0.09	0.45	0.07	0.36	0.02	0.30	0.03	0.11	0.03	0.04	0.02	0.07	0.06
6/2		1,695	20.8	0.80	0.80	0.70	0.15	0.70	0.20	0.55	0.02	1.4	0.03	0.66	0.01	0.36	0.01	0.12	0.02	0.03	0.02	0.04	0.04
6/3		2,260	24.7	0.80	0.70	0.60	0.10	0.90	0.20	0.30	0.02	0.85	0.03	0.68	0.02	0.63	0.02	0.24	0.02	0.07	0.02	0.05	0.04
				$\bar{X}$ 0.72	0.68	0.50	0.14	0.62	0.15	0.43	0.03	0.65	0.03	0.41	0.01	0.28	0.02	0.11	0.02	0.04	0.02	0.06	0.05
				S 0.13	0.13	0.16	0.02	0.18	0.05	0.18	0.03	0.50	0.03	0.27	0.01	0.24	0.01	0.09	0.01	0.02	0.01	0.02	0.02
6/5		12	0.5	1.0	0.9	1.0	0.27	1.1	0.20	0.14	0.02	0.12	0.03	0.08	0.02	0.04	0.02	0.03	0.02	0.04	0.02	0.05	0.04
6/6		565	24.6	0.80	0.7	0.80	0.06	0.70	0.04	1.1	0.01	0.88	0.02	0.35	0.01	0.13	0.01	0.05	0.02	0.04	0.03	0.05	0.04
6/7	2.5	1,130	22.7	1.0	0.9	1.3	0.02	0.8	0.08	0.36	0.02	1.3	0.20	0.70	0.02	0.35	0.02	0.11	0.15	0.07	0.03	0.04	0.04
6/8		1,695	25.0	0.8	0.8	0.80	0.52	0.60	0.37	0.08	0.01	0.1	0.01	0.38	0.01	0.21	0.02	0.11	0.02	0.04	0.03	0.03	0.04
6/9		2,260	24.0	0.8	0.8	0.80	0.60	0.60	0.45	1.1	0.01	0.36	0.01	0.19	0.01	0.11	0.02	0.07	0.02	0.03	0.02	0.03	0.04
				$\bar{X}$ 0.88	0.82	0.94	0.29	0.76	0.23	0.56	0.01	0.55	0.05	0.34	0.01	0.17	0.02	0.07	0.05	0.04	0.03	0.04	0.04
				S 0.11	0.08	0.22	0.26	0.21	0.18	0.51	0.01	0.52	0.08	0.24	0.01	0.12	0.00	0.03	0.06	0.01	0.10	0.01	0.00
Mean				$\bar{x}$ 0.77	0.71	0.74	0.17	0.67	0.29	0.75	0.02	0.78	0.03	0.33	0.01	0.19	0.02	0.09	0.04	0.04	0.02	0.05	0.04
Standard Deviation				s 0.13	0.13	0.24	0.17	0.17	0.51	1.11	0.02	0.95	0.05	0.23	0.01	0.18	0.02	0.06	0.08	0.01	0.01	0.02	0.02

T - total
S - Soluble

APPENDIX D
STATISTICAL ANALYSIS

Table D1. ANALYSIS OF VARIANCE OF RAW WATER SOLUBLE IRON CONCENTRATIONS

Source of Error	Sum of Squares	Degrees of Freedom	Mean Squares	Computed F
Days	0.674	4	0.168	0.77
Contact Time	1.762	2	0.881	4.02^{ns}
Error	1.534	7	0.219	
Total	3.970			

ns - no significant difference in raw water at 95% or 99% level of confidence

Table D2. ANALYSIS OF VARIANCE OF RAW WATER SOLUBLE MANGANESE CONCENTRATIONS

Source of Error	Sum of Squares	Degrees of Freedom	Mean Squares	Computed F
Days	0.033	4	0.008	0.68
Contact Time	0.114	2	0.057	4.74^{ns}
Error	0.081	7	0.012	
Total	0.228			

ns - no significant difference in raw water at 99% level of confidence

Table D3. ANALYSIS OF VARIANCE OF CONTACT COLUMN EFFLUENT SOLUBLE IRON CONCENTRATIONS

Source of Error	Sum of Squares	Degrees of Freedom	Mean Square	Computed F
Days	0.143	4	0.036	0.78
Contact time	0.095	2	0.047	1.02^{ns}
Error	0.366	8	0.046	
Total	0.604			

ns - no significant difference in treatment at 95% or 99% level of confidence

Table D4. ANALYSIS OF VARIANCE OF CONTACT COLUMN EFFLUENT SOLUBLE MANGANESE CONCENTRATIONS

Source of Error	Sum of Squares	Degrees of Freedom	Mean Squares	Computed F
Days	0.080	4	0.020	0.80
Contact time	0.120	2	0.060	2.40^{ns}
Error	0.198	8	0.025	
Total	0.398			

ns - no significant difference in treatment at 99% level of confidence

Table D5. ANALYSIS OF VARIANCE OF FILTER EFFLUENT TOTAL IRON CONCENTRATIONS

Source of Error	Sum of Squares	Degrees of Freedom	Mean Square	Computed F
Days	0.056	4	0.014	1.00
Contact time	0.326	2	0.160	11.43**
Error	0.100	7	0.014	
Total	0.482			

**significant difference in filter effluent at 99% level of confidence

Table D6. ANALYSIS OF VARIANCE OF FILTER EFFLUENT TOTAL MANGANESE CONCENTRATIONS

Source of Error	Sum of Squares	Degrees of Freedom	Mean Square	Computed F
Days	0.0031	4	0.0008	2.00
Contact time	0.0009	2	0.0005	1.25^{ns}
Error	0.0030	8	0.0004	
Total	0.0070			

ns - no significant difference in filter effluent at 95% or 99% level of confidence

APPENDIX E

AVERAGE IRON AND MANGANESE REMOVAL THROUGH PILOT SYSTEMS

Table E1. AVERAGE IRON REMOVAL THROUGH PILOT SYSTEMS

Sample Location (mg/l)	Pieterick Fe T	Pieterick Fe S	Stoebner Fe T	Stoebner Fe S	Schjodt Fe T	Schjodt Fe S	Kirscherman (Continuous) Fe T	Kirscherman (Continuous) Fe S	Kirscherman (Intermittent) Fe T	Kirscherman (Intermittent) Fe S
Raw Water	4.74	4.50	4.54	4.25	3.9	2.60	4.4	4.3	4.3	4.1
Filter Influent	5.02	0.15	4.3	0.03	3.7	0.02	2.7	0.06	2.2	0.14
Media Interface	3.10	0.10					1.4	0.03	0.96	0.10
Filter Effluent	0.14	0.05	0.24	0.03	0.03	0.02	0.07	0.04	0.09	0.08
Iron Removals (%)										
Raw Water										
Filter Influent	-5.9	96.7	5.3	99.3	5.1	99.20	38.60	98.6	48.8	96.6
Media Interface	40.5	1.1					29.50	0.7	28.8	1.0
Filter Effluent	62.4	1.1	89.4	0	94.1	0	30.20	-0.2	20.2	0.5
Total Removal	97.0	98.9	94.7	99.3	99.2	99.2	98.4	99.1	97.8	98.1

T - total
S - soluble

Table E2. AVERAGE MANGANESE REMOVAL THROUGH PILOT SYSTEMS

	Pieterick		Stoebner		Schjodt		Kirschenman (Continuous)		Kirschenman (Intermittent)	
	Mn		Mn		Mn		Mn		Mn	
Sample Location (mg/l)	T	S	T	S	T	S	T	S	T	S
Raw Water	0.88	0.82	0.64	0.64	2.3	2.3	0.6	0.6	0.59	0.59
Filter Influent	0.76	0.23	0.67	0.08	2.3	0.18	1.7	0.08	0.58	0.55
Media Interface	0.56	0.01					0.71	0.01	0.45	0.44
Filter Effluent	0.04	0.04	0.04	0.01	0.02	0.01	0.02	0.01	0.01	0.01
Manganese Removals (%)										
Raw Water										
Filter Influent	13.6	72.0	-4.7	87.5	0	92.2	-183.3	86.7	1.7	6.8
Media Interface	22.7	26.8					165.0	11.6	22.0	18.6
Filter Effluent	59.1	-3.7	98.4	10.9	99.1	7.4	115.0	0	74.6	72.9
Total Removal	95.4	95.1	93.7	98.4	99.1	99.6	96.7	98.3	98.3	98.3

T - total
S - soluble

APPENDIX F

FILTER HEAD LOSS

Table F1. STATIC HEAD ABOVE THE EFFLUENT WEIR 0.5 HOURS AFTER BACKWASH

Sample Tap	Location			Average Head Loss
1	Above Filter Media	2.50	2.42	2.46
2	Surface of Coal	2.50	2.37	2.43
3		2.42	2.29	2.35
4		2.29	2.17	2.23
5		2.13	2.04	2.08
6	Coal Greensand Interface	1.83	1.83	1.83
7		1.50	1.58	1.54
8		1.17	1.29	1.23
9		0.83	1.00	0.91
10		0.54	0.62	0.58
11		0.25	0.29	0.27
12	Bottom of Contact Bed	0.00	0.00	0.00

Filtration rate 2 gpm/ft^2, 6 inch (15 cm) diameter filter

Table F2. STATIC HEAD ABOVE THE EFFLUENT WEIR 12 HOURS AFTER BACKWASH

Sample Tap	Location					Average Head Loss
1	Above Filter Media	4.50	4.50	4.50	4.50	4.50
2	Surface of Coal	4.00	4.50	4.33	4.37	4.30
3		2.79	2.87	3.04	2.83	2.88
4		2.08	2.04	2.25	2.17	2.13
5		1.62	1.46	1.67	1.58	1.58
6	Coal Greensand Interface	air	air	air	air	air
7		1.00	0.87	0.96	0.96	0.95
8		0.83	0.71	0.79	1.08	0.85
9		0.67	0.54	0.62	0.58	0.60
10		0.50	0.37	0.46	0.42	0.44
11		0.33	0.21	0.29	0.29	0.28
12	Bottom of Contact Bed	0.08	0.04	0.04	0.08	0.06

[1]Filtration rate 2 gpm/ft^2, 6 inch (15 cm) diameter filter

Table F3. STATIC HEAD ABOVE THE EFFLUENT WEIR 24 HOURS AFTER BACKWASH

Sample Tap	Location					Average Head Loss
1	Above Filter Media	4.75	4.87	4.79	4.71	4.78
2	Surface of Coal	3.17	3.12	3.46	3.21	3.24
3		2.08	1.92	2.12	2.00	2.03
4		1.42	1.25	1.33	1.25	1.31
5		1.00	1.08	1.08	1.12	1.07
6	Coal Greensand Interface	0.75	0.54	0.67	0.58	0.63
7		0.54	0.46	0.46	0.67	0.53
8		0.46	0.42	0.42	0.33	0.41
9		0.37	0.33	0.33	0.33	0.34
10		0.33	0.29	0.29	0.29	0.30
11		0.25	0.25	0.25	0.25	0.25
12	Bottom of Contact Bed	0.12	0.21	0.21	0.21	0.19

[1]Filtration rate 2 gpm/ft^2, 6 inch (15 cm) diameter filter

APPENDIX G

COST CALCULATIONS

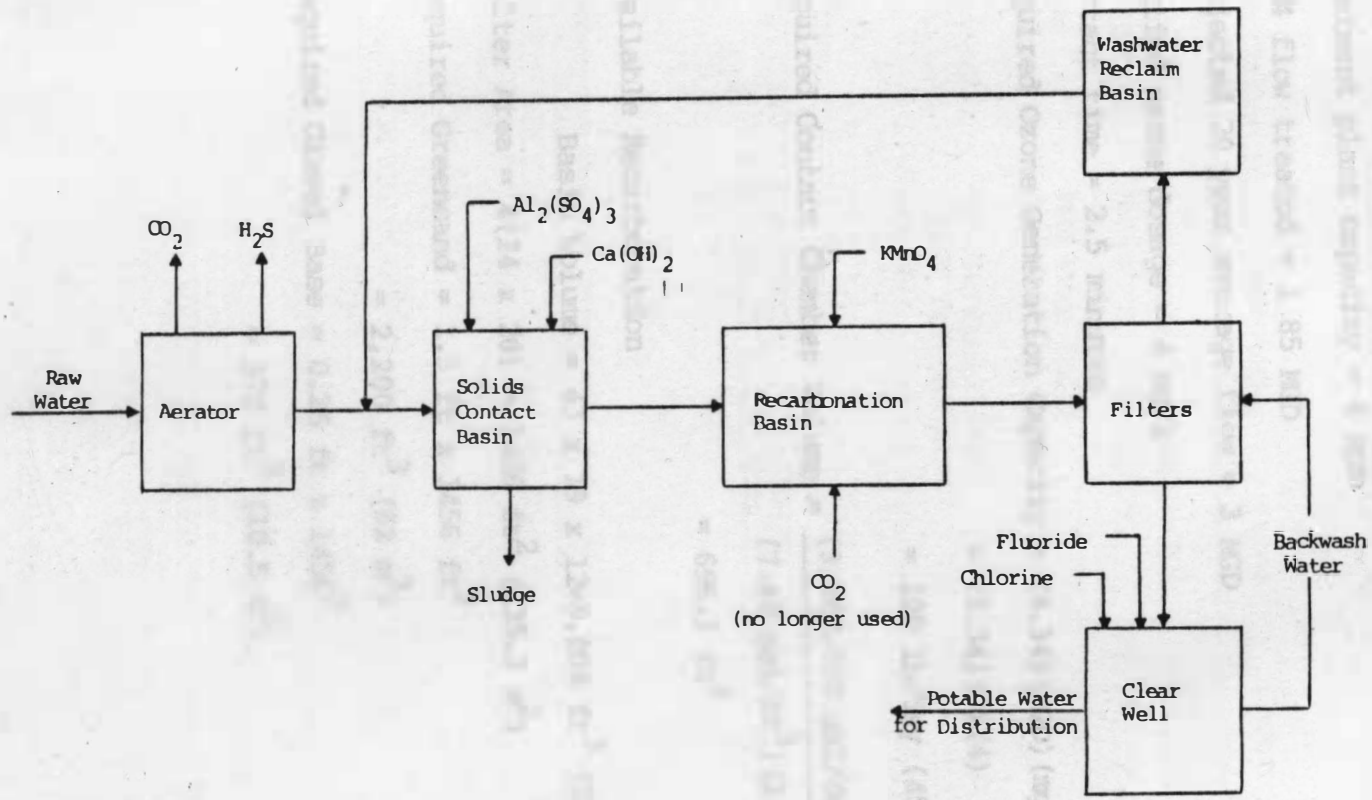

Figure G1. Flow Diagram of the Brookings East Water Treatment Plant

COST ESTIMATIONS

Treatment plant capacity = 4 MGD

1984 flow treated = 1.85 MGD

Projected 20 year average flow = 3 MGD

Applied ozone dosage = 4 mg/l

Contact time = 2.5 minutes

Required Ozone Generation Capacity = (8.34)(MGD)(mg/l)

= (8.34)(3)(4)

= 100 lb/day (45.5 kg/day)

$$\text{Required Contact Chamber Volume} = \frac{(3{,}000{,}000 \text{ gal/day})(2.5 \text{ min})}{(7.48 \text{ gal/ft}^3)(1440 \text{ min/day})}$$

$$= 696.3 \text{ ft}^3 \qquad (19.7 \text{ m}^3)$$

Available Recarbonation

Basin Volume = 43 x 19 x 12=9,804 ft^3 (277.4 m^3)

Filter Area = 4(14 x 26) = 1456 ft^2 (135.3 m^2)

Required Greensand = 1.5 ft x 1456 ft^2

= 2,200 ft^3 (62 m^3)

Required Gravel Base = 0.25 ft x 1456^2

= 370 ft^3 (10.5 m^3)

Table G1. COMPUTATION OF COST-UPDATING INDICIES

Cost Component	Cost Index	Oct. 1978 Index	Oct. 1984 Index	Jan. 1985 Index	Updating Index
Manufactured Equipment	BLS General Purpose Machinery and Equip.	221.3	316.1	-	1.43
Labor	ENR Wage Index for Skilled Labor	247.0	-	376.8	1.53
Maintenance Materials	BLS Producer Price Index for Finished Goods	199.7	291.6	-	1.46

Note: ENR = Engineering News Record
BLS = Bureau of Labor Statistics, U.S. Dept. of Labor

Table G2. COMPUTATION OF OZONATION COSTS

Cost Component	Cost as of October 1978 (dollars)	Updating Index	Cost Ending 1984 (dollars)
Construction Costs:			
Manufactured Equipment	152,350	1.43	217,960
Labor	35,410	1.53	54,180
Subtotal	187,760	-	272,140
Miscellaneous and Contingency (10% of subtotal)	18,780	-	27,220
Total Construction Cost	206,540	-	$299,360
Operation and Maintenance Cost:			
Maintenance Materials	2,800	1.46	4,090/yr
Electrical Energy (401,500 kw-hr/yr)($0.07/kw-hr)			28,100/yr
Labor (580 hr/yr)($12/hr)			6,960/yr
Total O & M Cost			$39,150/yr

Table G3. 1985 CONSTRUCTION COST FOR GREENSAND[1]

Material	Unit Cost	Quantity	Freight (dollars)	Cost (dollars)
Greensand	$23/ft^3	2,200 ft^3	1200	51,800
Fine Gravel	$75/ton	370 ft^3	-	1,100
Subtotal	-	-	-	52,900
Labor and Contingency (40%)				21,160
Total Construction Cost				$74,060

[1]Unit costs were provided by Tonka Equipment, Minneapolis, Minnesota

Table G4. ESTIMATE OF AVERAGE ANNUAL CHEMICAL COSTS FOR EXISTING WATER TREATMENT FACILTY[1]

Type of Chemical	Chemical Feed Rate for 1984 (ppm)	Unit Costs for 1984	Chemical Costs Per Year For 3 MGD Flow
Quicklime	96	$78.75/2000 lbs	34,520
Alum	6	$ 6.10/50 lbs	6,690
$KMnO_4$	0.125	$138.40/110 lbs	1,440
Polyphosphate	1.2	$ 1.30/lb	14,250
Subtotal			56,900
25% projected 20 year average inflation			14,230
Annual Average Chemical Cost			$71,130/yr

[1]Chemical application rates and unit costs were provied by the City of Brookings